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EFFECTS OF DEFLECTED WING TIPS ON THE AERODYNAMIC

CHARACTERISTICS OF A CANARD CONFIGURATION

AT MACH NUMBERS FROM 0.7 TO 3.5

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TECHNICAL MEMORANDUM X-392

EFFECTS OF DEFLECTED WING TIPS ON THE AERODYNAMIC CHARACTERISTICS OF A CANARD CONFIGURATION AT MACH NUMBERS FROM 0.7 TO 3.5*

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SUMMARY

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An investigation has been conducted to determine the effects on the untrimmed and trimmed aerodynamic characteristics of two canard airplane configurations resulting from the downward deflection of the wing tips about hinge lines parallel to the body center line. One configuration had an aspect-ratio-2 triangular-wing plan form for which the outboard 16 percent of the area was deflectable. The second was derived from the first by replacing the deflectable triangular-wing tips with untapered surfaces of twice the area having the same sweep as the wing leading edge. Experimental longitudinal and sideslip data were obtained for several Mach numbers ranging from 0.70 to 3.54.

The results showed that deflecting either the triangular tips or the swept tips significantly reduced supersonic longitudinal stability and increased directional stability. The effects on the stability were accompanied by reductions of lift-curve slope and increases in drag due to lift which resulted in reduced values of maximum untrimmed lift-drag ratio. Despite the detrimental effects of deflecting the tips on the maximum untrimmed lift-drag ratio, it is shown that the maximum trimmed lift-drag ratio can be either higher or lower with tips deflected than with tips undeflected, depending upon the stability level of the configuration with tips undeflected.

Estimations of the effects of the deflected tips on the untrimmed aerodynamic characteristics were generally in fair agreement with the experimental results.

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*Title, Unclassified

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INTRODUCTION

Among the aerodynamic problems associated with the characteristics of aircraft designed to fly at supersonic speeds are the increases of longitudinal stability and the reductions of directional stability resulting from increasing Mach number from subsonic to supersonic. The characteristic of increased longitudinal stability generally requires that the minimum static margin be set at subsonic speeds so that it is necessary to balance or overcome large out-of-trim moments at supersonic speeds. The second characteristic, concerning directional stability, introduces another problem - that of maintaining an adequate level of directional stability at supersonic speeds. Both of these problems can lead to inefficient configurations through the use of large longitudinal controls and vertical stabilizers.

The results of references 1 and 2 have shown for triangular wing configurations that one means of alleviating both problems is the deflection of the wing tips about essentially streamwise hinge lines at supersonic speeds. The rearward movement of the aerodynamic center is thereby reduced as a result of reducing the lifting area near the wing trailing edge. At the same time, additional vertical stabilizing area is provided in the Mach number range where it is needed.

The primary purpose of this investigation is to extend the results of reference 1, wherein the outboard 4 percent of the total area of each wing panel was deflected 90°. The present investigation determined the characteristics of a similar aspect-ratio-2 triangular plan form for which 16 percent of the total area of each wing panel could be deflected various amounts to 90°. A second configuration investigated was derived from the first by replacing the deflectable triangular tips with untapered surfaces having the same sweep as the wing leading edge and having twice the area of the triangular tips. The first configuration was investigated at Mach numbers from 0.70 to 3.54 and the second from 2.49 to 3.54. Both of the configurations were tested with and without a canard control. Comparisons of experimental and estimated effects on the aerodynamic characteristics resulting from deflecting the surfaces have been made.

NOTATION

a.c. aerodynamic center determined at $C_L = 0$, percent $\bar{c}$

Δa.c. aerodynamic-center location of a configuration with tips deflected minus that for the configuration with tips undeflected, percent $\bar{c}$

b wing span

$\bar{c}$ mean aerodynamic chord of the complete triangular wing

C_D drag coefficient, $\frac{\text{drag}}{qS}$

C_{D_o} drag coefficient at $C_L = 0$

$\left(\frac{C_D}{C_L^2}\right)$ drag-due-to-lift factor, determined as average rate of change of C_D with C_L^2 between $C_L = 0$ and $C_L = 0.2$

$\Delta\left(\frac{C_D}{C_L^2}\right)$ drag-due-to-lift factor for configuration with tips deflected minus that for the configuration with tips undeflected

C_L lift coefficient, $\frac{\text{lift}}{qS}$

C_{L_α} lift-curve slope taken through 0° angle of attack, per deg

ΔC_{L_α} lift-curve slope for configuration with tips deflected minus that for the configuration with tips undeflected, per deg

C_m pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$, referred to the projection of the 0.21 $\bar{c}$ point on the body reference line

C_l rolling-moment coefficient, $\frac{\text{rolling moment}}{qSb}$

C_n yawing-moment coefficient, $\frac{\text{yawing moment}}{qSb}$, referred to the projection of the 0.21 $\bar{c}$ point on the body reference line

C_Y side-force coefficient, $\frac{\text{side force}}{qS}$

ΔC_n yawing-moment coefficient for configuration with tips deflected minus that for the configuration with tips undeflected

ΔC_Y side-force coefficient for configuration with tips deflected minus that for the configuration with tips undeflected

C_{l_β} difference between rolling-moment coefficient at 5° sideslip angle and 0° sideslip divided by 5°, per deg

C_{n_β} difference between yawing-moment coefficient at 5° sideslip angle and 0° sideslip divided by 5°, per deg

[redacted]

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C_{Y_β}	difference between side-force coefficient at 5° sideslip angle and 0° sideslip divided by 5°, per deg
l	theoretical length of body
$\frac{L}{D}$	lift-drag ratio, $\frac{C_L}{C_D}$
M	free-stream Mach number
q	free-stream dynamic pressure
r	local body radius
r_o	maximum body radius
S	area of the complete triangular wing formed by extending the leading and trailing edges to the plane of symmetry
x	distance measured aft of body nose
α	angle of attack of wing root chord, deg
β	sideslip angle measured between the relative wind and the vertical plane of symmetry, deg
δ	angle of deflection of the canard, positive when trailing edge is down, deg
φ	angle of deflection of the wing tips, positive when tips are below plane of wing, deg

Configurations are denoted by the following letters used in combination:

B	body
C	canard
T_{xx}	designated tip deflection where xx is tip deflection angle φ, deg
V	vertical tail
W_1	triangular plan-form wing
W_2	triangular wing with tips removed at 60-percent semispan
W_3	W_2 with sweptback tips added

[redacted]

Subscripts

max	maximum value of quantity
t	value obtained with configuration trimmed

APPARATUS AND MODEL

Test Facilities

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The experimental data were obtained in the Ames 6- by 6-Foot Supersonic Wind Tunnel and the 8- by 7-foot test section of the Ames Unitary Plan Wind Tunnel. The 6- by 6-foot wind tunnel is a closed-circuit variable-pressure type with a nominal Mach number range continuous from 0.7 to 2.2. The tunnel floor and ceiling have perforations to permit transonic testing. The Unitary Plan Wind Tunnel is also a closed-circuit variable-pressure type and the 8- by 7-foot test section has a nominal Mach number range continuous from 2.5 to 3.5.

Description of Model and Balance

The basic sting-mounted model (fig. 1) consisted of an aspect-ratio-2 triangular wing, an aspect-ratio-2 triangular canard, and a low-aspect-ratio vertical tail mounted on a fineness-ratio-12.5 Sears-Haack body. The wing had hexagonal streamwise sections which were 3 percent thick between the 30-percent and 70-percent chord stations. The streamwise included angles of the leading- and trailing-edge wedges were 5.74°.

The model referred to as the "triangular tips configuration" had deflectable triangular surfaces which consisted of the area of each wing panel outboard of the 60-percent-semispan location (16 percent of the total panel area) and which could be deflected downward at various angles up to 90° about a hinge line parallel to the body center line or could be removed entirely. A dimensional sketch of this configuration is shown in figure 1(c). The second model referred to as the "swept tips configuration" was derived by replacing the deflectable triangular wing tips with untapered surfaces having the same sweep as the wing leading edge and having twice the area of the triangular tips (32 percent of the total area of each triangular wing panel). The sweptback tips could be deflected downward at angles to 90° or could be removed entirely. A dimensional sketch of this configuration is shown in figure 1(d).

The canard was constructed from a flat plate 0.20 inch thick and had leading and trailing edges beveled to form included streamwise angles of 5.2° and 9.5°, respectively. The canard hinge line, passing through the 0.35 point of its mean aerodynamic chord, was mounted in the extended wing chord plane 1.21 wing mean aerodynamic chord lengths ahead of the reference center of moments ($0.21\ \bar{c}$). The ratio of the area of the exposed canard panels to the total area of the wing was 6.9 percent and the ratio of the total areas was 12.9 percent. The vertical tail had NACA 0003-63 sections streamwise. The ratio of the exposed area of the tail to the total area of the wing was 13.9 percent. All the model components were constructed of solid steel to minimize aeroelastic effects. A

The body was cut off as shown in figure 1 to accommodate the sting and the internal, six-component, strain-gage balance which measured forces and moments on the entire configuration. 351

TEST AND PROCEDURES

Ranges of Test Variables

Data were obtained at Mach numbers of 0.70, 0.90, 1.30, 1.70, 2.22, 2.49, 3.06, and 3.54, both at angles of attack and sideslip. The exact test conditions for each configuration are shown in table I. The test Reynolds number based on the triangular wing mean aerodynamic chord was 3.68 million. For test Mach numbers below 2.49, wires of 0.010-inch diameter were placed on both surfaces of the wing and on the body, and wires of 0.005-inch diameter were placed on both surfaces of the vertical tail and canard at the locations shown in figure 1(c) in order to induce transition at fixed locations on the model. The wire sizes were selected on the basis of the results of reference 3. No wires were placed on the model for Mach numbers of 2.49 and above, since the wire size required to induce transition results in excessive pressure drag.

Reduction of Data

The data presented herein have been reduced to coefficients based on the geometry of the complete triangular wing. The pitching- and yawing-moment coefficients have been referred to the projection, on the body center line, of the 0.21 point of the triangular wing mean aerodynamic chord. Lift and drag coefficients were referred to the wind axes while all other coefficients have been referred to the body axes.

The base pressure was measured and the data were adjusted to correspond to a base pressure equal to the free-stream static pressure.

The data obtained in the Ames 6- by 6-Foot Supersonic Wind Tunnel were adjusted for a stream inclination of less than $\pm 0.30^{\circ}$ which existed throughout the Mach number range of the tests. Similar corrections were made for the data obtained in the 8- by 7-foot test section of the Ames Unitary Plan Wind Tunnel, where the stream inclination was less than 0.21° over the range of test Mach numbers.

The drag data obtained in the 8- by 7-foot test section were corrected for the buoyancy effect of longitudinal static-pressure variations in the vicinity of the model. These corrections amounted to less than 1.6 percent of the zero lift drag of the model. It was not necessary to make buoyancy corrections to the data obtained in the 6- by 6-Foot Supersonic Wind Tunnel.

RESULTS AND DISCUSSION

The primary purpose of the present investigation was to evaluate and compare experimental and estimated effects on the aerodynamic characteristics of two wing and body combinations resulting from the deflection, at supersonic speeds, of area about essentially streamwise hinge lines located at 60 percent of the semispans. Certain experimental results of reference 1 are included herein for the purpose of showing the effect on some of the characteristics of the amount of wing area deflected 90°.

The estimated results were obtained from linear theory with wing-body interference effects accounted for in general by the methods outlined in reference 4. Estimations have been made only for configurations without the canard since no theory is available to accurately predict the interference effects of the canard on the wing, body, and vertical tail. It should be noted that for the estimations of longitudinal characteristics presented herein wing-body interference was determined for a finite length afterbody rather than for the infinite afterbody used in reference 1.

Longitudinal Characteristics

The lift, drag, and pitching-moment characteristics of the triangular tips configuration with tips undeflected, deflected, and removed are presented in figure 2 with the canard off and in figures 3 through 5 with the canard on. The same characteristics for the swept tips configuration with the tips undeflected, deflected, and removed are presented in figure 6 with the canard off and in figure 7 with the canard on.

Aerodynamic center.- The aerodynamic-center locations of the canard-off configurations with either the triangular or swept tips at various angles of deflection or removed are shown in figure 8 as a function of Mach number. Examination of figure 8(a) shows that for the triangular wing and body combination of this investigation ($\varphi = 0^{\circ}$) the difference between the aerodynamic-center location at 0.70 Mach number and supersonic speeds could be large, depending upon the supersonic Mach number. This difference attained the greatest value at a Mach number of 1.30 where it amounted to 0.105 $\bar{c}$ and it decreased with increasing supersonic Mach number to 0.019 $\bar{c}$ at a Mach number of 3.54.

Further examination of figure 8 reveals that deflecting the tips
about streamwise hinge lines at supersonic speeds is an effective A
method for shifting the aerodynamic-center location forward. For the 3
triangular tips the results of figure 8(a) show that the largest forward 5
shifts of the aerodynamic center obtained without removing the tips 1
entirely occurred when the tips were completely unloaded ($\varphi = 90^{\circ}$). Furthermore, the amounts of the forward shifts decreased with increasing supersonic Mach number. Throughout the test Mach number range the changes in the aerodynamic-center location incurred by removing the undeflected tips were larger than the changes incurred by deflecting the tips 90°. These differences in the amounts of the aerodynamic-center shifts can probably be attributed to the effects of the wing side edge on the characteristics of the fixed portion of the wing which are apparently more pronounced when the tips are off than when the tips are in the 90° position (see ref. 1). The possibility also exists that the air stream was not exactly alined with the hinge line as a result of the flow past the expanding body nose. This would cause the 90° deflected tips to induce a pressure field on the underside of the undeflected portion of the wing.

A more detailed examination of the pitching-moment curves throughout the lift-coefficient range shows an interesting characteristic that is apparently related to the wing side edge or tip effects when the tips are deflected. The results of figure 2(e), for example, show that the difference between the stability of the configuration with tips at 90° and the configuration with tips removed is considerably less at negative lift than at positive lift. Because of model symmetry this suggests the possibility that upward deflected tips, by virtue of not being so effective in suppressing the wing side-edge effect, would provide greater forward aerodynamic-center shifts at positive lift coefficients than would downward deflected tips.

For the swept tips the results of figure 8(b) show the forward aerodynamic-center shifts to be greater for each angle of deflection than for the deflected triangular tips. However, even though the area of the swept tips is twice as large as that of the triangular tips and is distributed farther aft on the configuration, the forward aerodynamic-center shifts are not larger by a factor of 2. This might be expected since the swept surfaces themselves have tip effects which prevent them from carrying as much load per unit area as do the triangular tips.

It is important to determine what effects, if any, the addition of the canard control has on the forward aerodynamic-center shifts experienced as a result of deflecting the outboard surfaces. These effects are shown in figure 9(a) for both 90° deflection and complete removal of the triangular tips and in figure 9(b) for 60° deflection of the swept tips. The effectiveness of deflecting outboard surfaces to achieve forward aerodynamic-center shifts is increased measurably with the
A addition of the canard at 0° deflection. Two possible reasons for this
3 result are readily apparent. The first and probably most important
5 reason for the increase in tip effectiveness with the addition of the
1 canard is related to the fact that the aerodynamic-center of the configuration is at a more forward location, relative to the tips, when the canard is on than when the canard is off. This relative spacing between the tips and the configuration aerodynamic-center has an effect for the same reasons that the difference between the stick-fixed and stick-free stability of any configuration is dependent on the relative locations of the control and center of lift of the other aerodynamic surfaces. The second reason why the aerodynamic-center shifts are larger when the canard is on than when it is off might be related to the differences between the canard-wing interference when the tips are undeflected and when they are deflected or removed. It is thus evident from the results of figure 9 that for this particular configuration a lesser amount of wing tip deflection angle would be required to produce a given aerodynamic center shift when the canard is on than when it is off.

It is of interest to determine how well the effects on the aerodynamic-center location resulting from deflecting the tips can be estimated. In reference 1 it was shown that good estimations of the forward aerodynamic-center shifts resulting from 90° deflection of the outboard 4 percent of the area of each triangular-wing panel could be obtained by assuming that the deflected tips completely suppressed the linear theory planar tip effect of reference 5, or, in other words, that the pressure on the fixed portion of the wing was unchanged by tip deflection. Therefore, for this analysis, the aerodynamic center of the configuration with tips deflected 90° is estimated by calculating the aerodynamic center of the trapezoidal wing with planar tip effects omitted. When the outboard surfaces are removed entirely, the tip effects are included. The results of these calculations are shown in figure 9 wherein the forward aerodynamic center shifts resulting from deflecting the tips to 90° or removing them entirely are presented as a function of Mach number. The effects on the aerodynamic center due to 90° deflection of either the triangular tips or the swept tips are predicted reasonably well throughout the Mach number ranges investigated. The forward aerodynamic-center shifts due to removing the tips are also closely predicted at all Mach numbers.

It has been shown that the forward aerodynamic-center shifts resulting from deflecting the tips 90° can be estimated reasonably accurately. It is still necessary to predict the aerodynamic-center shifts due to intermediate angles of tip deflection. Two approaches to this problem are readily apparent. One approach would be to consider the variation with tip angle of attack of the force normal to the surface of the tip to be invariant with tip deflection angle. Then, since both the angle of attack of the tip and the force normal to the wing chord plane vary as the cosine of φ, the lift on the tip would be reduced A
approximately as $\cos^2\varphi$. In the second approach the lift on the tip is 3
allowed to vary directly as the area of the tip projected onto the plane 5
of the undeflected portion of the wing. In effect, this method allows 1
the lift on the tip to be reduced as $\cos\varphi$. The first method described above was orginally presented in reference 2 and will be referred to as the nonplanar method. The second approach will be referred to as the planar method. The experimental results are compared with both of these methods in figure 10 wherein the ratios of forward aerodynamic-center shifts resulting from intermediate tip deflection are shown as a function of tip deflection angle, φ, for Mach numbers of 2.49 and above. It should be noted that the estimated curves for $M = 3.06$ only were presented in figure 10 since the curves for the other Mach numbers considered showed less than a ±4-percent deviation from these values. The variation of this parameter with deflection angle φ is predicted well for both types of tips by the planar method or, in other words, by the method which assumes the tip lift to vary as the first power of the cosine of deflection angle, φ. It is interesting to note that when the tips are deflected 60°, only half of the total possible aerodynamic-center shift has occurred.

It is readily apparent that the methods used in calculating both the variation of the aerodynamic center movement with tip deflection angle φ and the absolute magnitude of the shift for 90° of tip deflection are by no means exact within the limits of linear theory. An attempt was made to treat the problem in a more precise manner by the superposition of two conical flow solutions; one for the triangular wing and one for the tip surface. Inherent in this method was the assumption that the pressure along any ray from the apex of its conical flow field was unchanged by turning through the angle between the undeflected portion of the wing and the deflected tip surface. The results of these calculations were not included herein since the aerodynamic-center shift resulting from 90° of tip deflection did not, in general, agree as favorably with the experimental data as did the results for the method presented; the predicted variation of aerodynamic-center movement with tip deflection angle φ was close to that given by the nonplanar method.

The forward aerodynamic center-shift that can be obtained by deflecting outboard portions of the wing is a function not only of the angle of deflection of the surfaces but also the amount of area of the wing that is movable. The measured effects of the amount of area deflected 90°, determined by combining results from reference 1 with those obtained in this investigation, are compared with the estimated effects in figure 11 for several Mach numbers. It should be noted that for supersonic Mach numbers for which the leading edge of the wing is subsonic ($M \leq 2.24$), Mach number has very little effect on the estimated variation of forward aerodynamic-center shift so that the single estimated curve shown in figure 11 applies to the three Mach numbers in this range. Estimated results for Mach numbers above 2.24 do show a Mach number dependence, however. The experimental data show a Mach number dependence which is not predicted. This probably results from some tip effect acting at least on the upper surface of the undeflected portion of the wing when the tips are deflected. The results of figure 11 also show that the rate of change of forward aerodynamic-center shift with amount of area deflected is becoming somewhat smaller as more area is deflected. This trend is a result of the center of pressure of the load on the area being deflected approaching the center of pressure of the load on the triangular wing as the amount of area deflected is increased.

Lift and drag.- The lift-curve slopes of the canard-off configurations with the tips either at various angles of deflection or removed are shown in figures 12(a) and 12(b) as functions of Mach number for the triangular and swept tips, respectively. Examination of figure 12 shows the expected trend of reduced lift-curve slopes due to tip deflections at all Mach numbers investigated. It is also shown that without the tips the lift-curve slopes are less than the values for 90° tip deflection. This latter trend is consistent with the previously discussed effect of removing the tips on the aerodynamic center - they both indicate the planar tip effect is suppressed by the deflected tips.

The effects on the lift-curve slopes resulting from either 90° deflection or removal of both the triangular and swept tips have been estimated. The comparisons of these estimates with the experimental results are made in figure 13 wherein the variation with Mach number of the ratios of lift-curve slopes with tips deflected 90° or removed to lift-curve slopes of the configurations with tips at 0° are presented. The agreement is good at the lower Mach numbers and excellent at the higher ones. This generally good agreement tends to substantiate the assumption based on the results of reference 1 that the 90° deflected tips suppress the planar tip effects.

Also shown in figure 13 is the effect of the addition of the canard on the lift-curve-slope ratio for the configuration with the triangular tips deflected 90° or removed or with the swept tips deflected 60°.

The effect of the canard on this parameter is never large nor is it consistent with Mach number. This strongly suggests that the large consistent effects of the addition of the canard on the aerodynamic center shifts are a result of the previously discussed relative locations of the center of tip lift and the aerodynamic-center locations with the canard on and off rather than differences between canard-wing interference when the tips are undeflected and when they are deflected or removed.

Figure 14 presents the experimental and estimated effects of tip deflection angle φ on lift-curve slope. The results shown in this figure are similar to those shown for aerodynamic-center shifts discussed previously; namely, that only half of the total change of the lift-curve slope with deflection angle has occurred when the tips are deflected 60° and that the planar estimates are in better agreement with the experimental results.

If the present results are combined with those of reference 1, the effects on the lift-curve slopes resulting from the 90° deflection of various amounts of wing area can also be shown. These experimental effects are presented in figure 15 together with the estimated effects. At Mach numbers below 2.24 where the wing leading edge is subsonic, the percentage reduction of lift-curve slope due to removing wing area by 90° tip deflection is nearly twice the percentage reduction of the wing area; for example, 90° deflection of 16 percent of the wing area results in approximately a 30-percent reduction of lift-curve slope. However, as the Mach number is increased above that for a sonic leading edge, experiment and theory indicate the percentage reduction of lift-curve slope decreases for a constant amount of deflected area.

Deflection of either the triangular tips or the swept tips resulted in pronounced effects on the lift and pitching-moment characteristics and it would be expected that the drag would likewise be affected primarily through effects on the drag due to lift. The effects on the minimum drag coefficient and drag due to lift resulting from deflecting the surfaces are shown in figure 16 as a function of Mach number. Deflection of either the triangular or the swept tips had little effect on the minimum drag, in fact so little that only the extremes of 0° and 90° deflection angles are shown.

The drag due to lift was increased significantly throughout the Mach number range as a result of deflecting the tips. The complete removal of the tips produced further increases in the drag due to lift of about the same magnitude as those obtained for 90° tip deflection. These increases can be attributed primarily to the reductions of lift-curve slope. Since the sharp wing leading edge does not permit the attainment of a significant amount of the leading-edge thrust predicted by linear theory when the wing leading edge is subsonic, the estimates here of the effects on the drag due to lift resulting from either deflecting the tips 90° or removing them were made assuming no leading-edge suction throughout the Mach number range. These estimates are compared with the experimental results in figure 17. In general, the estimated increases in the drag due to lift are larger than those obtained experimentally. At some Mach numbers this condition exists partly as a result of the overestimate of the reduction of lift-curve slope. Another contributing factor to this disagreement between estimated and experimental results is the nonlinearity of the lift with increasing angle of attack (e.g., see fig. 2) believed to be caused primarily by the tendency of the sharp wing leading edge to promote leading-edge separation. While the nonlinear increase in lift due to leading-edge separation at a given angle of attack is probably reduced somewhat by deflecting the tips, it evidently amounts to a greater percentage of the total lift when the surfaces are deflected or removed. Thus, as the angle of deflection of the tips is increased, the error resulting from estimating the drag due to lift by assuming a linear variation of lift with angle of attack would be increased.

Included in figure 17 are data showing the effect of the addition of the canard on the drag-due-to-lift increases resulting from tip deflection or tip removal. In general, the canard has the effect of reducing the drag-due-to-lift increase, the greatest effect being when the tips are removed completely.

Although the theory generally overestimated the increase in drag due to lift resulting from deflecting the tips 90°, it is still interesting to determine if the effects at intermediate deflection angles can be estimated knowing the values of the drag due to lift at 0° and 90° tip deflection. The estimated variations with tip deflection angle φ of the change in drag due to lift expressed as a fraction of the total drag due to lift change for 90° of deflection for both the planar and nonplanar methods are compared with the experimental variations in figure 18. It should again be noted that the estimated curves for $M = 3.06$ only were presented in figure 18 since the curves for the other Mach numbers considered showed less than a ±4-percent deviation from these values. The results of figure 18 are consistent with the lift and pitching moment results discussed previously inasmuch as deflections of the order of 60° produce about half the total possible change in drag due to lift and also the planar estimates afford the best agreement with the experimental data.

The drag-due-to-lift results of reference 1 have been combined with the present results to determine the variation with percent of wing area deflected 90° of the drag due to lift for the triangular tips. The experimental variations shown in figure 19 for several Mach numbers are also compared with the estimated variations. The drag due to lift is increasing steadily with increasing percentage of wing area deflected as a result of the reducing lift-curve slope although the experimental increases are always less than that which would be expected from lift-curve slope considerations alone. The experimental results of figure 19 for Mach numbers of 2.22 and below also show a dependence on Mach number which is not predicted by the theory.

It is appropriate to summarize the over-all effects of the deflected tips on the lift and drag of the configurations by examining the variations with Mach number of the maximum lift-drag ratios. The maximum lift-drag ratios of the canard off configuration with either the triangular tips or swept tips at the various angles of deflection or removed are presented in figure 20 as a function of Mach number. The maximum lift-drag ratios are shown to be always decreasing with increasing deflection angle. While the lift and drag characteristics of the configurations with tips deflected 90° and with tips removed were quite different at all Mach numbers investigated, the lift-drag ratios of these two configurations were nearly the same for Mach numbers of 2.49 and above. This is due primarily to the fact that at these higher Mach numbers the reduction in minimum drag coefficient resulting from removing the tips nearly compensates for the increased drag due to lift.

<u>Trimmed characteristics</u>.- Deflecting the tips of a triangular wing has been shown to be a powerful method for reducing the configuration longitudinal stability at supersonic speeds, but the attendant losses in maximum untrimmed lift-drag ratio could reduce the attractiveness of using this method. A compensating factor does exist, however, in that the smaller out-of-trim moments when the tips are deflected would result in smaller increments of trim drag. Thus, it is possible that the trimmed lift-drag ratios obtained with the tips deflected would be higher than the trimmed lift-drag ratios obtained with the tips undeflected. Therefore, the lift-drag ratios of the triangular tips configuration trimmed with the canard will be examined. Both the center-of-gravity location and the variation with Mach number of the aerodynamic-center location of the configuration with tips undeflected have important effects on the determination of what tip deflection angles are needed at supersonic speeds to provide the most efficient trimmed configuration. For this analysis the chosen center-of-gravity location ($0.21\ \bar{c}$) of the configuration with the tips undeflected and the canard on at 0° deflection results in a static margin which is never less than about 4-percent $\bar{c}$ throughout the lift-coefficient range at 0.70 Mach number. With this center-of-gravity location the resulting minimum static margins at supersonic Mach numbers could be reduced to nearly zero with 90° of tip deflection at Mach numbers through 2.22 and 60° tip deflection at Mach numbers from 2.49 to 3.54 (see figs. 4 and 5). The lesser amount of required tip deflection at the higher Mach numbers is a result of the rather large forward movement of the aerodynamic center with Mach number of the configuration with the tips undeflected. These tip deflection angles for which trimmed characteristics were obtained are not necessarily the optimum for this particular configuration but the

results do demonstrate the effects on the trimmed lift-drag ratios when the static margins are reduced by about the maximum amount permissible without allowing the configuration to become unstable. It should be noted that in the higher Mach number range trimmed characteristics for the configuration with 0° of tip deflection were obtained by assuming that the canard characteristics measured in reference 6 apply to the present canard. The configuration of reference 6 was identical to the triangular wing configuration of this investigation with the exception of wing section.

The trimmed lift-drag ratios for the deflected tips configurations are compared with those for the undeflected tips configuration in figure 21. The maximum trimmed lift-drag ratio was increased by about 0.8 at a Mach number of 1.30 as a result of deflecting the tips to 90°. However, the beneficial effects on the maximum trimmed lift-drag ratio resulting from deflecting the tips diminished with increasing Mach number until at a Mach number of 2.22 the maximum trimmed lift-drag ratio was the same with the tips either deflected or undeflected. At the higher Mach numbers the maximum trimmed lift-drag ratios were from 0.2 to 0.4 less when the tips were deflected 60° than when the tips were undeflected.

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Data were obtained for sufficient canard deflection angles at Mach numbers of 2.22 and below to examine the effects of static margin on the ratio of maximum trimmed lift-drag ratio with the tips deflected 90° to that for the undeflected tips. These results are shown in figure 22. The zero-lift static margin of 10.8-percent $\bar{c}$ at a Mach number of 0.70 corresponds to the 0.21 $\bar{c}$ center-of-gravity location for which the results have been discussed. Increasing the static margin above this level produces the favorable effect of increasing the maximum lift-drag ratio for the deflected tip configuration more and more above that for the undeflected tip configuration. Thus for airplane configurations in which the center-of-gravity location is farther forward or in which the favorable forward shift in aerodynamic-center location with increasing supersonic Mach number is not experienced it is possible that the trimmed lift-drag ratio may be increased by deflecting the wing tips at the higher supersonic Mach numbers as well.

Because of the twofold purpose of deflecting the tips, that is, to reduce the longitudinal stability and increase the directional stability at supersonic speeds, there is no doubt as to the desirability of deflecting the tips so long as the maximum trimmed lift-drag ratios are improved or at least equaled by so doing. However, when a reduction of the trimmed longitudinal efficiency of the configuration results from deflecting the tips, it then becomes necessary to examine the directional stability characteristics to determine if they are sufficiently improved to justify the possible penalties incurred in trimmed lift-drag ratio.

Lateral and Directional Characteristics

At Mach numbers of 2.22 and below all of the lateral and directional data (C_l, C_Y, C_n) were obtained at constant sideslip angles of 0° and 5° with angle of attack as the primary variable. At Mach numbers of 2.49 and above, the data were obtained at constant angles of attack of 0° and 5° with angle of sideslip as the independent variable. These results are presented in figures 23 through 27 and the ranges of the test variables are tabulated in table I. The lateral and directional incremental derivatives for the triangular tips configuration with the canard off are summarized as a function of Mach number in figure 28 for angles of attack of 0°, 5°, and 10° and for the canard-off swept tips configuration in figure 29 at 5° angle of attack.

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Examination of figures 28 and 29 shows that 90° deflection of either the triangular or the swept tips produced increases in C_{Y_β} which resulted in increased directional stability at all Mach numbers investigated. At Mach numbers of 2.49 and above, where data were available for intermediate angles of tip deflection, both C_{Y_β} and C_{n_β} increased with increasing tip deflection angle as would be expected. In contrast, the lateral stability derivative C_{l_β} exhibited a variation with tip deflection which was different from that which might be expected from a cursory analysis. The greatest change in C_{l_β}, and hence greatest reduction in lateral stability, occurred for 60° of tip deflection. As the tip angle was increased from 60° to 90° the lateral stability increased above the level for 60° of tip deflection. This reversal of the effect on C_{l_β} with increasing tip deflection angle can be related to the fact that the normal loads on the tips increase with increasing tip angle while the effective moment arms of these loads decrease with increasing tip angle. The tip angle where the reversal occurs is that angle where the increase in normal loads is exactly offset by the reduced moment arm lengths. Although the lateral stability was reduced considerably at large angles of tip deflection the triangular tip configuration still retained a margin of lateral stability ($-C_{l_\beta}$) for all Mach numbers investigated. However, deflection of the larger swept tips caused the lateral stability to be reduced to zero for 30° and 90° of tip deflection and less than zero for intermediate angles (see fig. 29).

An examination of the variation with angle of attack of the directional stability parameter C_{n_β} for the triangular tips configuration (fig. 28) reveals the fact that at supersonic speeds 90° deflection of the tips results in a greater percentage increase in stability at 5° angle of attack than at 0° angle of attack. This, combined with the reduction with increasing angle of attack of the vertical tail contribution to the directional stability (see ref. 7), results in a nearly constant stability level for the 90° deflected tips configuration for an angle of attack range of 0° to 5°. At larger angles of attack the stability decreases at about the same rate as when the tips are at 0°.

It has been shown in reference 7 and elsewhere that the effectiveness of a vertical stabilizing surface may be changed by the addition of a canard control because of interference between the canard-vortex field and vertical surface. Therefore, it is of importance to determine the extent of the effects of interference between the canard wake and downward deflected wing tips. These effects are shown in figure 30 for 5° angle of attack with the triangular tips deflected 90° at Mach numbers up to 2.22 and with tips deflected 60° in the Mach number range from 2.49 to 3.54. The results of figure 30 show that adding the canard had essentially no effect on the increments of side force or yawing moment at Mach numbers of 2.22 or less due to 90° of tip deflection. However, at Mach numbers of 2.49 and above, where the tips were deflected 60°, the addition of the canard control resulted in an increased level of directional stability. While the difference between the canard wing-tip interference might be related to Mach number effects it is believed to be more likely attributed to several factors related to tip deflection angle. Among them are the variation with tip deflection angle of the relative locations of the vortex field and deflected surfaces and the fact that when the tips are deflected to any angle other than 0° or 90°, they carry combined loadings due to angle of attack and angle of sideslip, both of which can be altered by interference-induced angles.

Although the canard has no effect on the increment of directional stability resulting from the 90° deflection of the tips at supersonic Mach numbers to 2.22, a study of the results of figure 23 indicates that it does affect the over-all stability level of the entire configuration at angles of attack above 6° to 10° depending upon the Mach number. This effect is destabilizing at a Mach number of 1.30, very small at $M = 1.70$, and slightly stabilizing at $M = 2.22$.

It is interesting to note in this regard that even if the effects of interference between the canard and other configuration components are destabilizing directionally, the net stability level of a canard configuration might still be higher than for an aft-control arrangement. This is due to the fact that the use of a canard control necessarily requires the center of gravity of the configuration to be at a more forward location to insure static longitudinal stability than if an aft control were used. This, in turn, causes the effective moment arm and hence directionally stabilizing effect of the loadings on the aft-located stabilizing surfaces to be greater for the canard configuration in the absence of interference effects.

[redacted]

The variation with Mach number of the experimental ratios at 0° angle of attack of C_{Y_β} and C_{n_β} with the triangular tips at 90° to C_{Y_β} and C_{n_β} with the tips at 0° are compared with estimates in figure 31. The estimates of these ratios were made using the method outlined in reference 1 wherein it is assumed that the wing acts as a reflection plane for the loading on the inboard sides of the deflected tips while the loading on the outboard side of each tip was assumed to correspond to that which the surface would carry in a free-stream environment. The C_{Y_β} ratio is predicted reasonably well at Mach numbers of 1.30 and 1.70 with increasing differences between experiment and theory noted at the higher Mach numbers. Of more significance, however, is the better agreement between the estimated and experimental directional stability ratios at all Mach numbers tested.

The changes in C_Y and C_n resulting from intermediate angles of tip deflection expressed as a fraction of the total changes in these parameters for 90° of tip deflection have also been estimated by means of both the planar and nonplanar methods described in the section on longitudinal characteristics. These estimates are compared with the experimental results for the triangular tips for an angle of attack of 0° at a Mach number of 3.06 in figure 32. The experimental side-force ratio is best approximated by the planar method while the yawing-moment ratio is predicted closely by the nonplanar method. Neither method of estimating these ratios appears to be superior and since both give results which are not greatly different for the larger angles of tip deflection the planar method results should probably be accepted on the basis of the close approximations of the longitudinal results by this method.

Again results from reference 1 have been used to show the effects on the directional stability resulting from the 90° deflection of various amounts of wing area. These effects are shown in figure 33 for 0° angle of attack and Mach numbers of 1.30, 1.70, and 2.22 and indicate a nearly linear increase in directional stability with amount of area deflected for all Mach numbers considered. It is further shown that the theory predicts this increase in a satisfactory manner for these Mach numbers.

It has been shown that the deflection of outboard portions of the triangular wing about streamwise hinge lines can result in large increases in directional stability. It has further been shown that the increases in directional stability may or may not be achieved without incurring penalities in the form of reduced maximum trimmed lift-drag ratio. Therefore, no definitive statement can be made as to the desirability of tip deflection as a means of improving directional stability without weighing the relative effects of the deflected tips on both the longitudinal and directional characteristics.

[redacted]

Combined Longitudinal and Directional Characteristics

The relative effects of the deflected tips on both the trimmed lift-drag ratios and the directional stability are summarized in figure 34. The values of directional stability used in this plot were obtained at the corresponding angles of attack for maximum trimmed lift-drag ratio. The results of figure 34(a) show for Mach numbers of 2.49 and above that 60° deflection of the tips increased the directional stability from about 1.6 to 2.3 times, depending upon the Mach number, while causing the maximum trimmed lift-drag ratios to be of the order of 93 to 95 percent of the values for no tip deflection.

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The results of figure 34(b) for supersonic Mach numbers of 2.22 and below and for 90° of tip deflection show that increases in directional stability of the order of 1.7 times could be achieved without any penalty in maximum trimmed lift-drag ratio when 16 percent of the wing area was deflected. In fact, at a Mach number of 1.30 the maximum trimmed lift-drag ratio was increased by about 15 percent. When the combined areas of the 90° deflected tips was less than 16 percent of the wing area, the increases of directional stability were correspondingly smaller and the maximum trimmed lift-drag ratio was penalized somewhat at $M = 2.22$. One of the factors contributing to the reduction with increasing Mach number of the beneficial effects of the 90° deflected tips on the maximum trimmed lift-drag ratio is the forward shift with increasing Mach number of the wing-body-canard aerodynamic-center location which is not experienced by many similar configurations. Without this forward aerodynamic-center shift the static margin of the undeflected tips configuration would be larger, thus increasing the possibility of improving the maximum trimmed lift-drag ratio by deflecting the tips. Another factor contributing to the reduction with increasing Mach number of the longitudinal benefits derived from deflection of the wing tips is the fact that the canard control itself becomes a more efficient trimming device at the higher Mach numbers than, for instance, trailing-edge flaps (see ref. 7), thereby offsetting to a certain extent the penalties incurred by having to trim against a large static margin.

One question that might arise in the design of an actual airplane concerns how much area should be deflected to what angle. During the course of analyzing the present data it has become apparent that this depends on the levels of longitudinal and directional stability possessed by the particular configuration. However, the general statement can be made that if a large increase in directional stability is needed while only a moderate reduction of longitudinal stability is necessary, then a comparatively large area should be deflected to an angle somewhat less than 90°. For example, only about one half of the forward aerodynamic center shift that would be obtained for 90° of tip deflection results from 60° of deflection (see fig. 10) while the 60° deflected tips provide about 80 percent of the maximum increment of directional stability which would result from 90° of tip deflection (see fig. 32). On the other hand, if both large increases in directional stability and large reductions in longitudinal stability are needed, then the tips should be deflected to 90° to obtain the maximum effects from the smallest amounts of deflected area. It thus becomes evident that the attainment of the optimum benefits, throughout a wide supersonic speed range, from the deflection of a fixed amount of area would likely require a variation of the tip deflection angle with Mach number.

CONCLUSIONS

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An investigation has been conducted to determine the effects on the untrimmed and trimmed aerodynamic characteristics of a canard airplane configuration resulting from the deflection, about hinge lines parallel to the body center line, of the outboard 16 percent of the area of each wing panel. The results of this investigation are as follows:

1. The increase of longitudinal stability experienced by the airplane configuration as the Mach number was increased from subsonic to supersonic could be completely eliminated throughout the supersonic test Mach number range by deflecting the tips to various angles.

2. Increasing the angle of tip deflection caused reductions in lift-curve slope and increases in drag due to lift which resulted in decreasing values of maximum untrimmed lift-drag ratio.

3. The directional stability was increased with increasing tip deflection angle at all Mach numbers.

4. Deflecting the tips permitted the maximum trimmed lift-drag ratios to be either higher than or equal to those obtained with the tips undeflected for Mach numbers between 1.30 and 2.22 while the directional stability at the trimmed angles of attack was increased about 70 percent. At Mach numbers between 2.49 and 3.54 the maximum trimmed lift-drag ratios were from 7.5 to 5 percent lower than those obtained with the tips undeflected but the directional stability at the trimmed conditions was increased from 64 to 126 percent, respectively.

5. Estimations of the effects of the deflected tips on the untrimmed aerodynamic characteristics were generally in fair agreement with the experimental results.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., June 20, 1960

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TABLE I.- RANGES OF TEST VARIABLES AND INDEX TO PLOTTED DATA

(a) Configurations with triangular tips and tips removed

Configuration	Mach number range	Angle-of-sideslip range, deg	Angle-of-attack range, deg	Canard δ, deg	Plotted data figure no.
BVW_1T_0	0.70 - 3.54	0	-10 to +18	--	2
	0.70 - 2.22	5	-6 to +18	--	23
	3.06	-7 to +7	0	--	24
	2.49 - 3.54	-7 to +7	5	--	25
BVW_1T_{60}	2.49 - 3.54	0	-10 to +15	--	2
	3.06	-7 to +7	0	--	24
	2.49 - 3.54	-7 to +7	5	--	25
BVW_1T_{75}	2.49 - 3.54	0	-10 to +15	--	2
	3.06	-7 to +7	0	--	24
	2.49 - 3.54	-7 to +7	5	--	25
BVW_1T_{90}	0.70 - 3.54	0	-10 to +18	--	2
	0.70 - 2.22	5	-6 to +18	--	23
	3.06	-7 to +7	0	--	24
	2.49 - 3.54	-7 to +7	5	--	25
BVW_2	0.70 - 3.54	0	-10 to +18	--	2
	2.49 - 3.54	-7 to +7	5	--	25
BVW_1T_0C	1.30 - 2.22	0	-6 to +18	0,4.6,9.6,20.0	3
	0.70 - 2.22	5	-6 to +18	0	23
$BVW_1T_{60}C$	2.49 - 3.54	0	-10 to +15	0,5	5
	2.49 - 3.54	-7 to +7	5	0,5	26
$BVW_1T_{90}C$	1.30 - 2.22	0	-6 to +18	0,5.1,9.6,20.0	4
	1.30 - 2.22	5	-6 to +18	0	23
(b) Configurations with sweptback tips					
BVW_3T_0	2.49 - 3.54	0	-10 to +15	--	6
	2.49 - 3.54	-7 to +7	5	--	27
BVW_3T_{30}	3.06	0	-10 to +15	--	6
	3.06	-7 to +7	5	--	27
BVW_3T_{60}	2.49 - 3.54	0	-10 to +15	--	6
	2.49 - 3.54	-7 to +7	5	--	27
BVW_3T_{75}	2.49 - 3.54	0	-10 to +15	--	6
	2.49 - 3.54	-7 to +7	5	--	27
BVW_3T_{90}	2.49 - 3.54	0	-10 to +15	--	6
	2.49 - 3.54	-7 to +7	5	--	27
BVW_3T_0C	2.49 - 3.54	0	-10 to +15	0	7
$BVW_3T_{60}C$	2.49 - 3.54	0	-10 to +15	0,5	7

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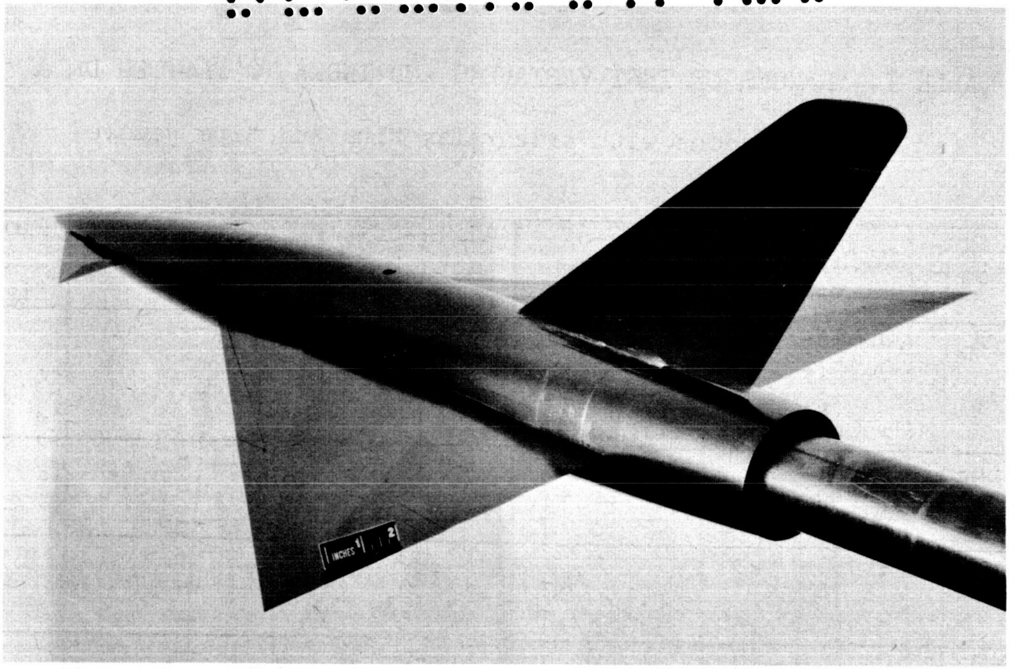

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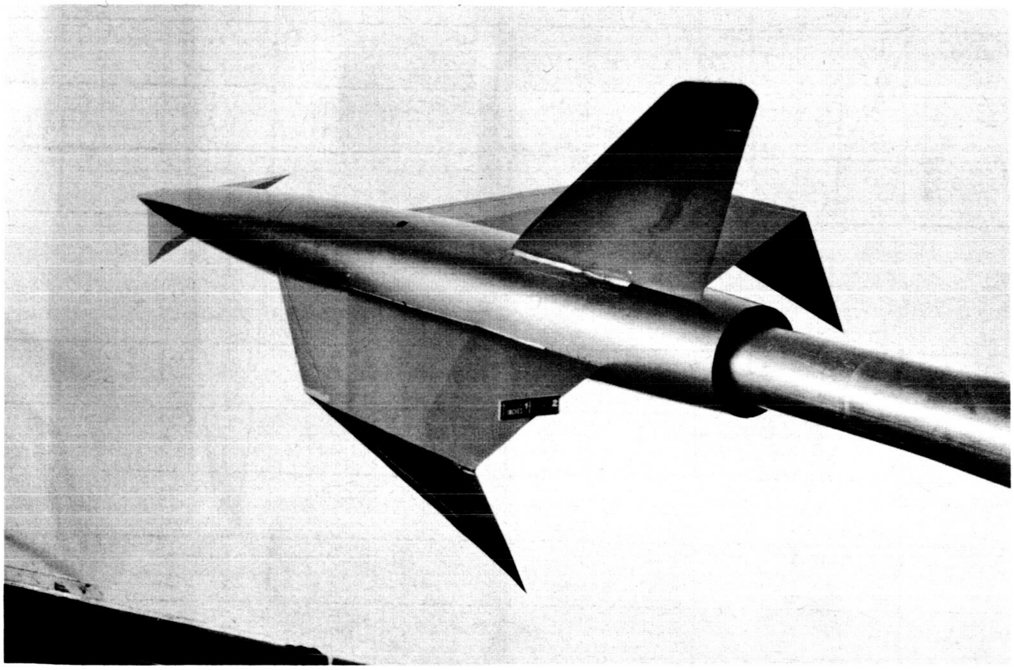
(a) Photograph of model with triangular tips undeflected.



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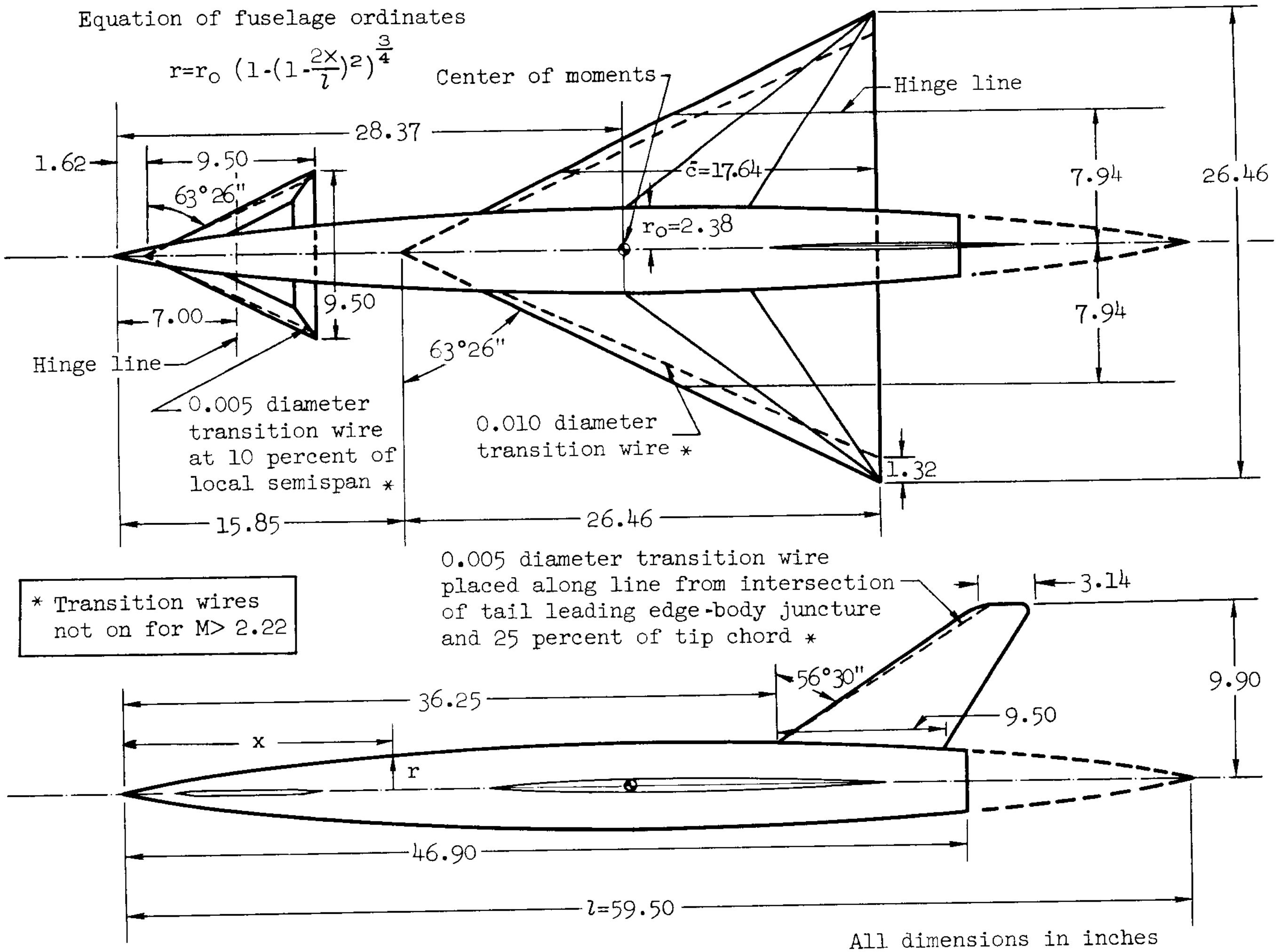
(b) Photograph of model with triangular tips deflected 90°.

Figure 1.- Model details and dimensions.

[redacted]



(c) Dimensional sketch of model with triangular wing tips.

Figure 1.- Continued.

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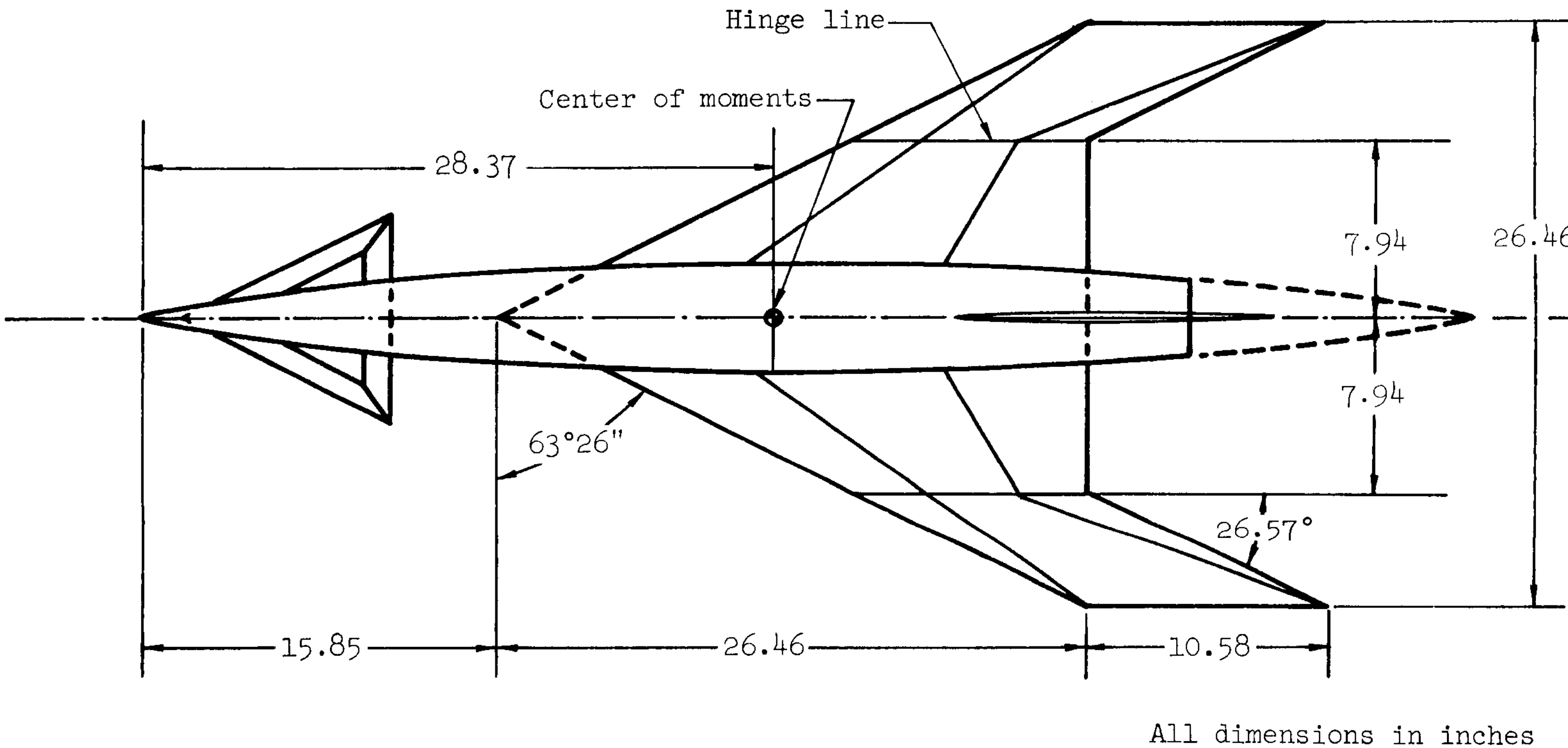

(d) Dimensional sketch of model with sweptback wing tips.

Figure 1.- Concluded.

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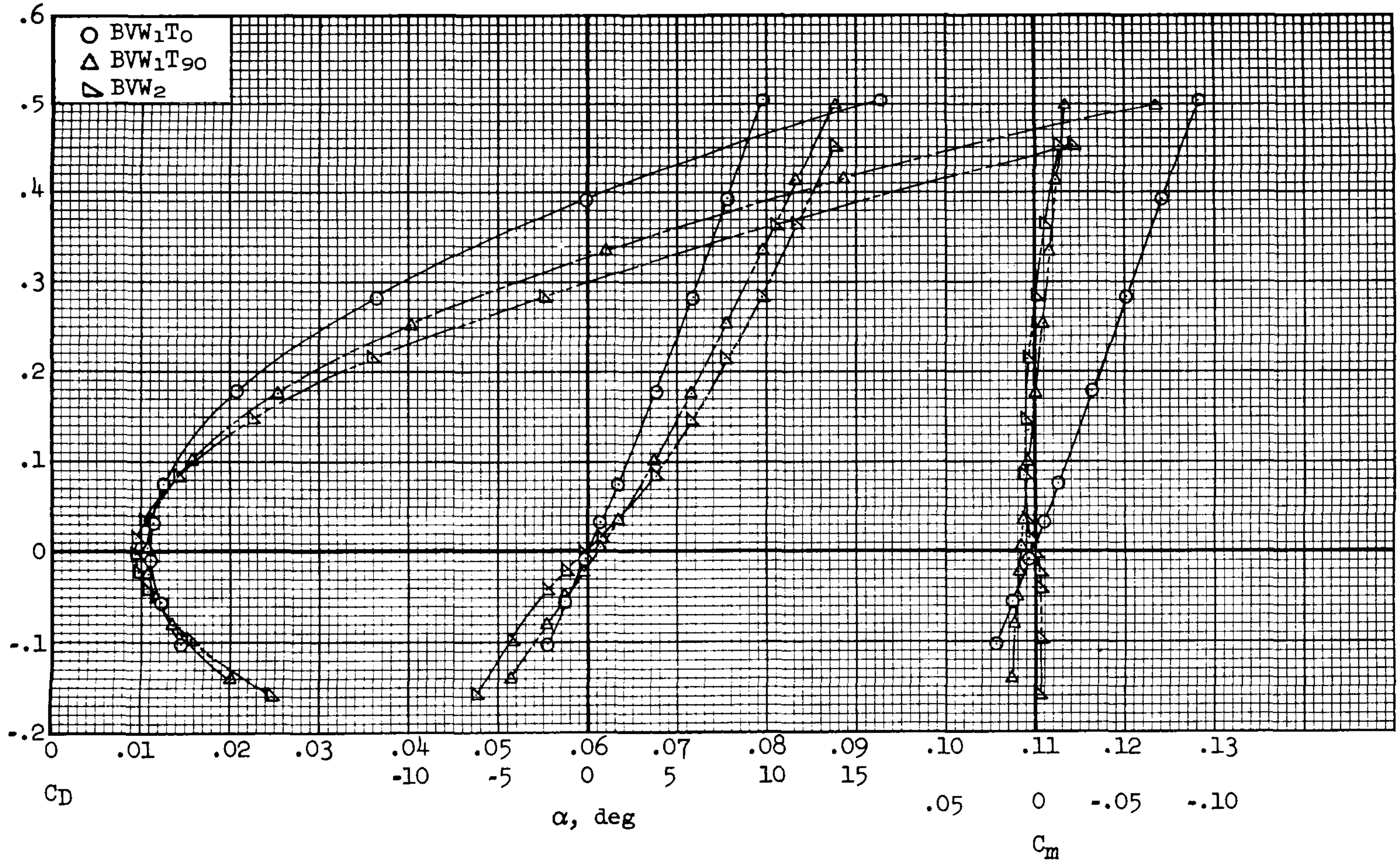

(a) M = 0.70

Figure 2.- Effect of various wing tip configurations on the longitudinal aerodynamic characteristics of the model, canard off.

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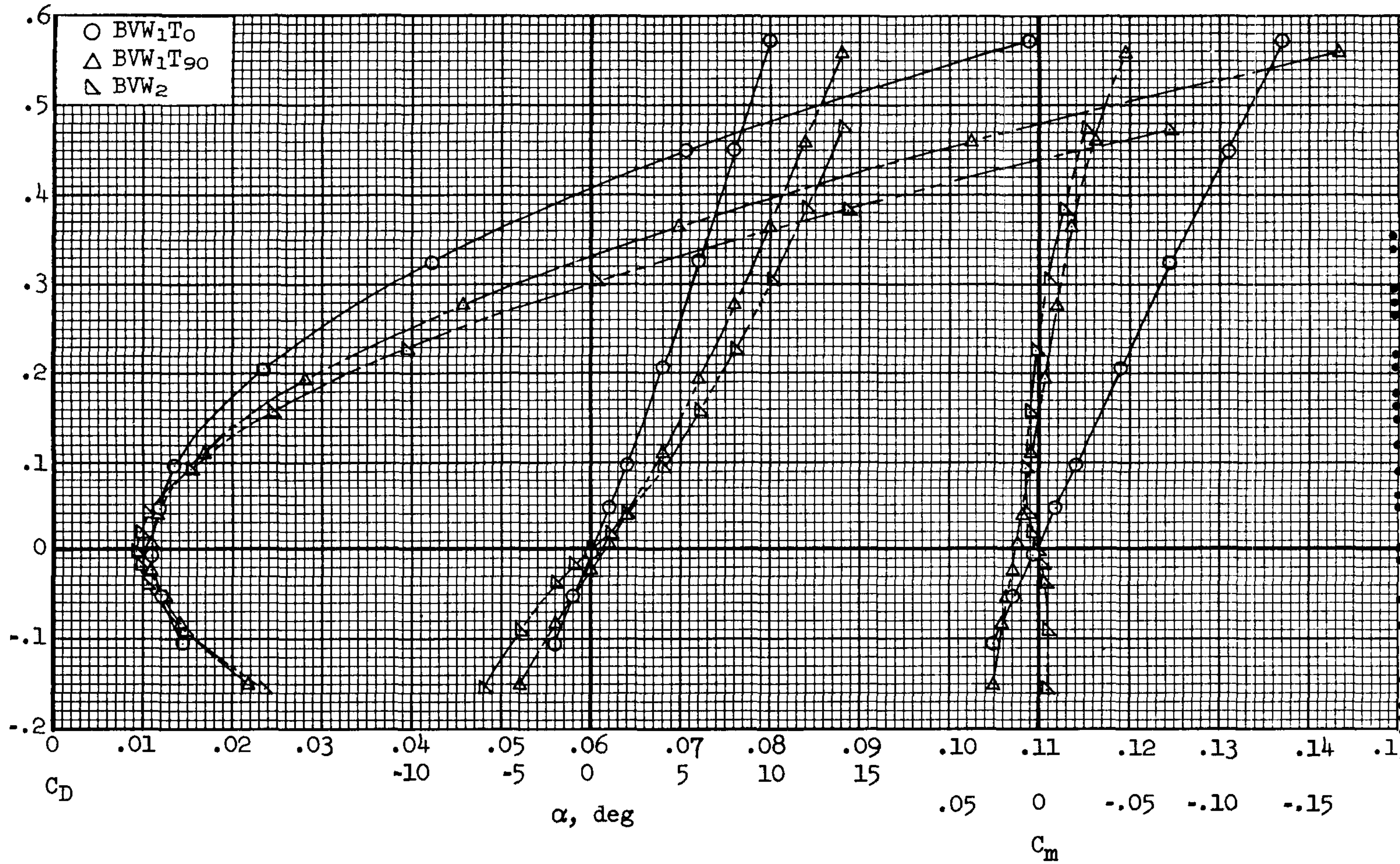
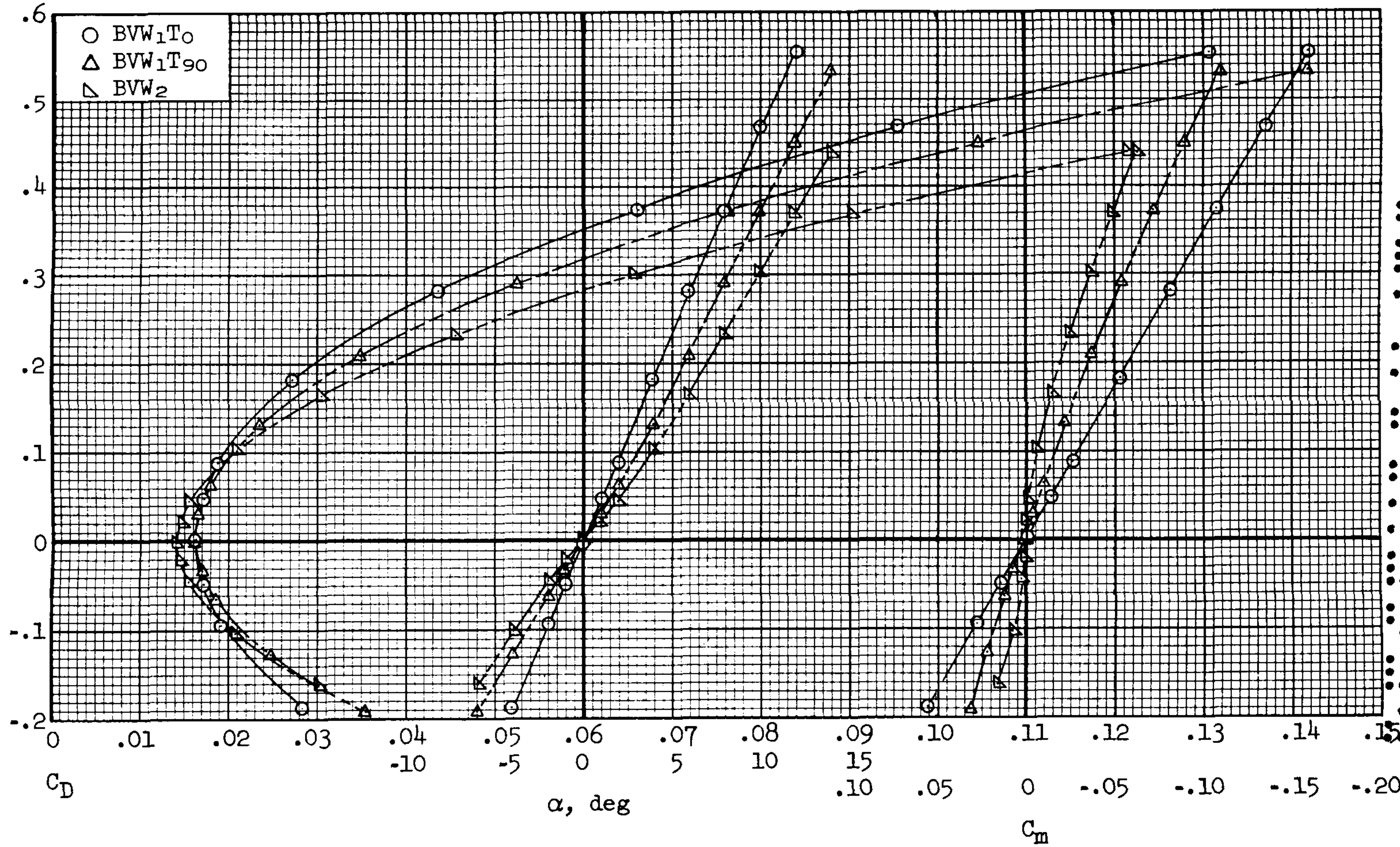


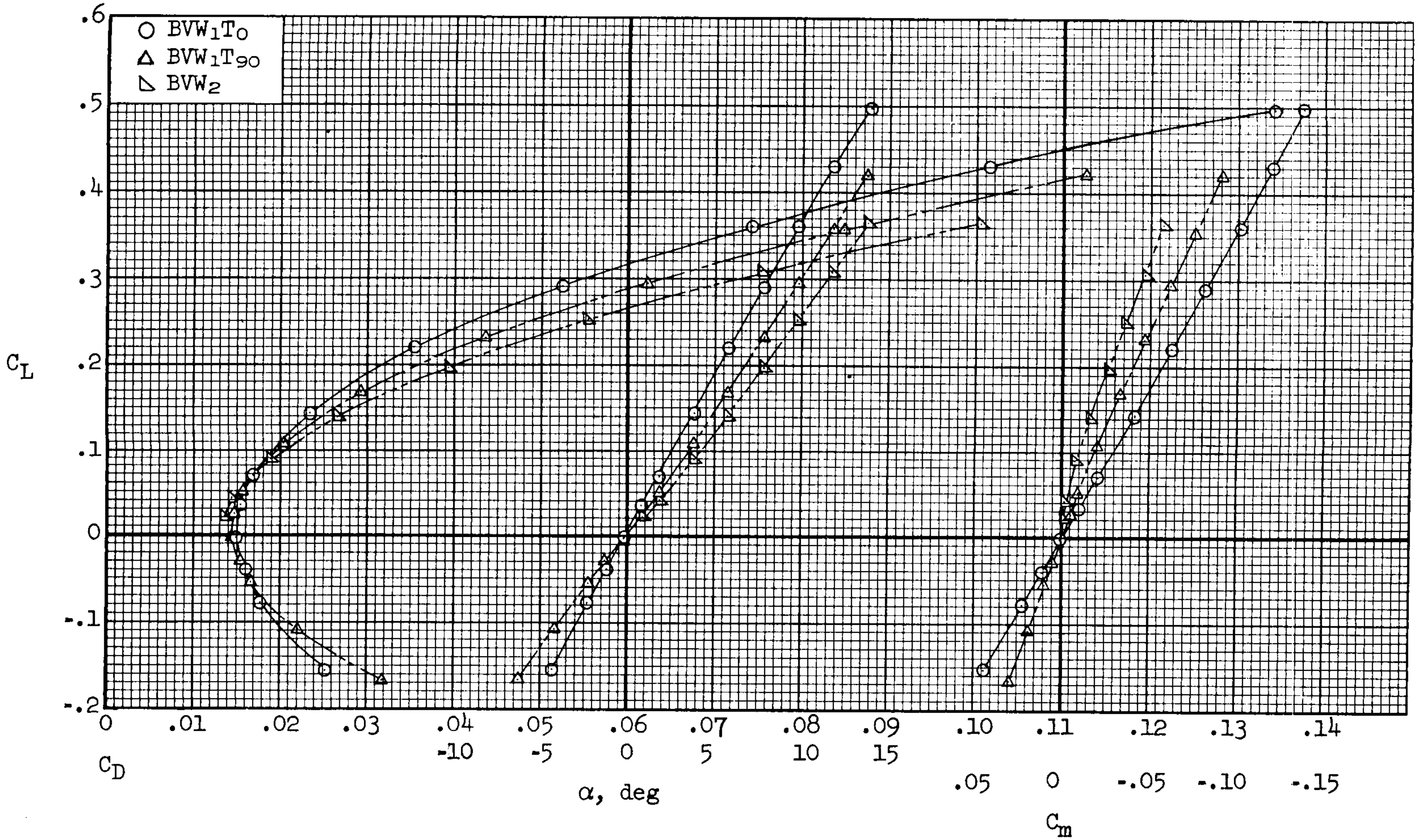
(b) M = 0.90

Figure 2.- Continued.



(c) M = 1.30

Figure 2.- Continued.



(d) M = 1.70

Figure 2.- Continued.

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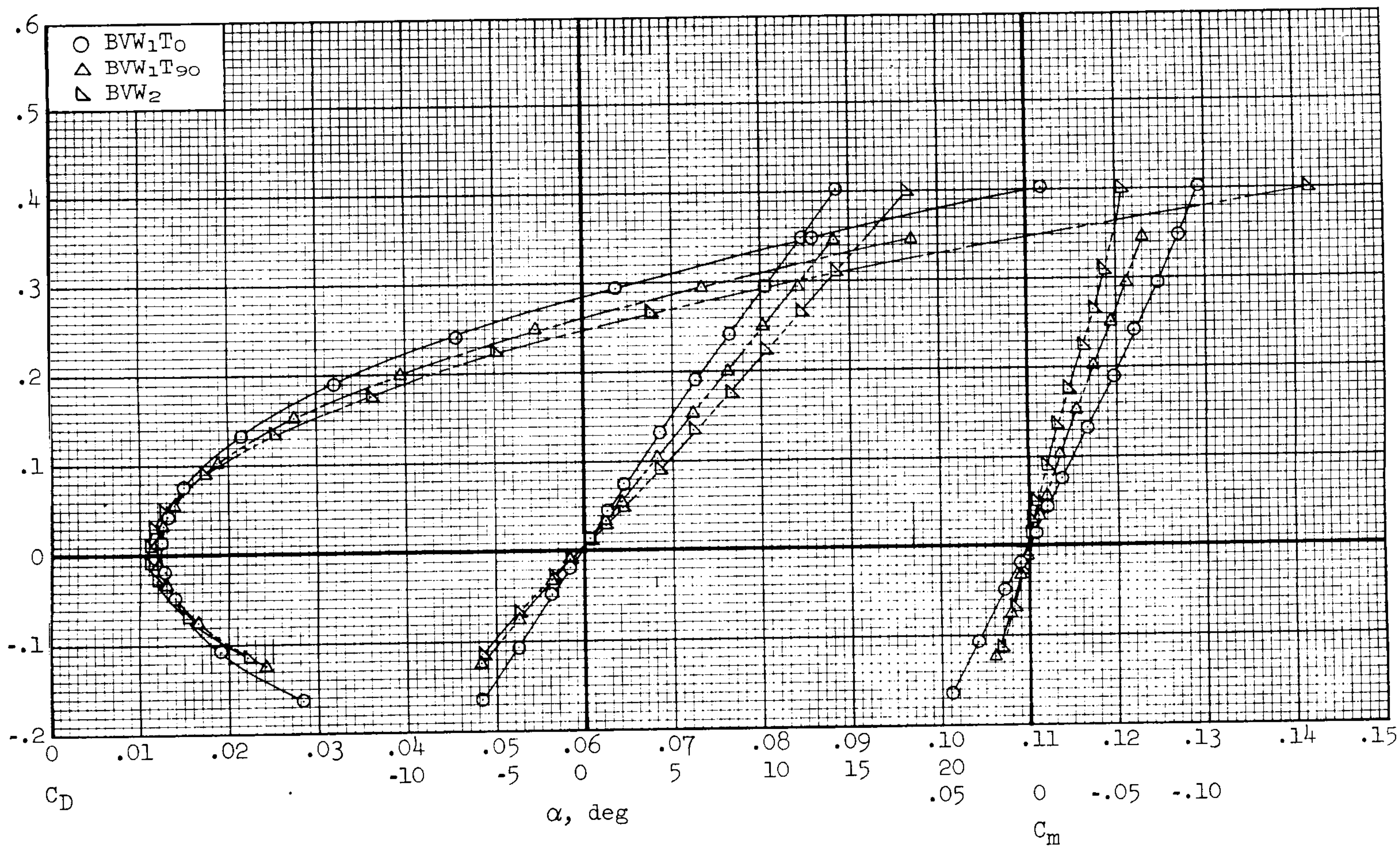

(e) M = 2.22

Figure 2.- Continued.

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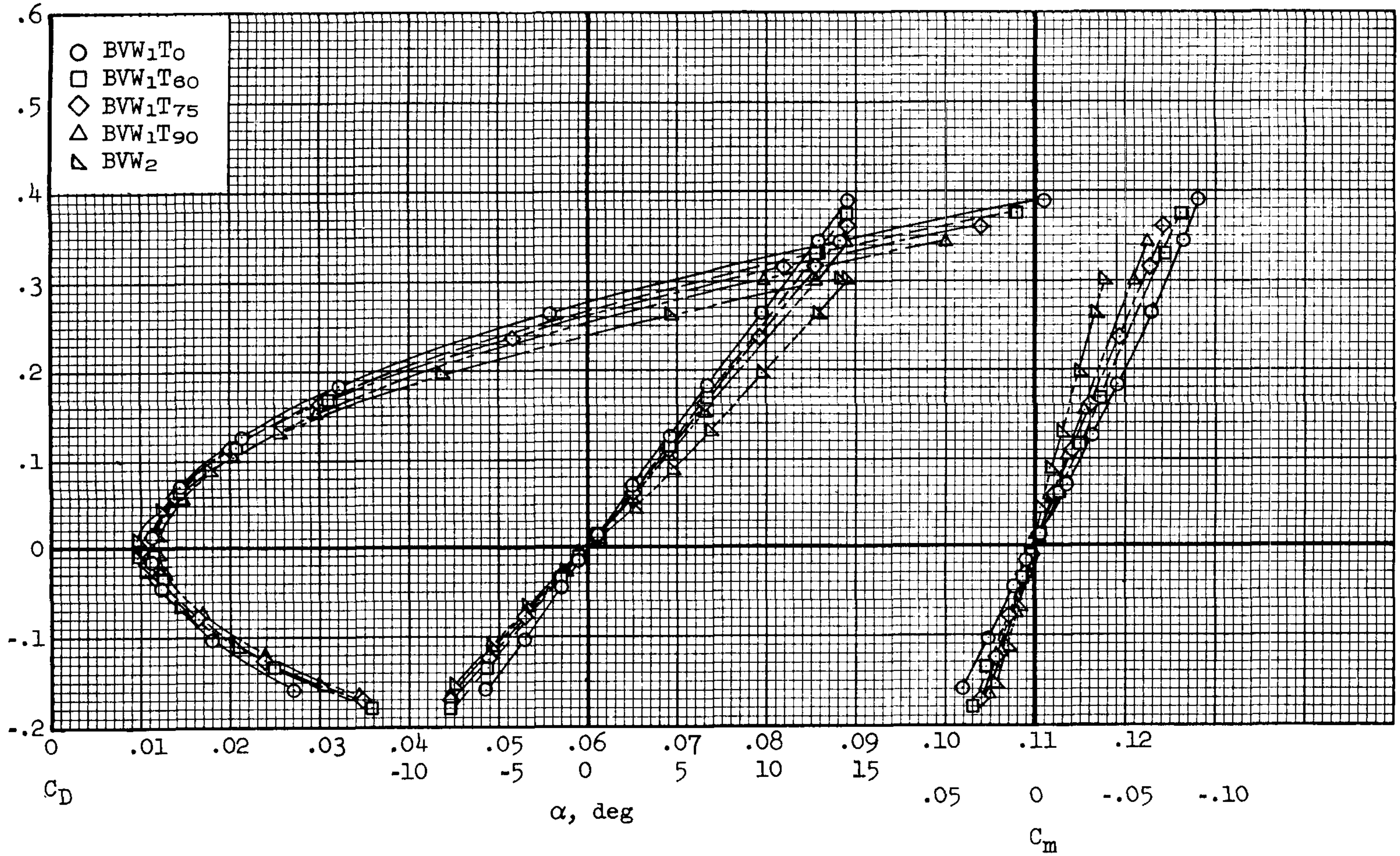

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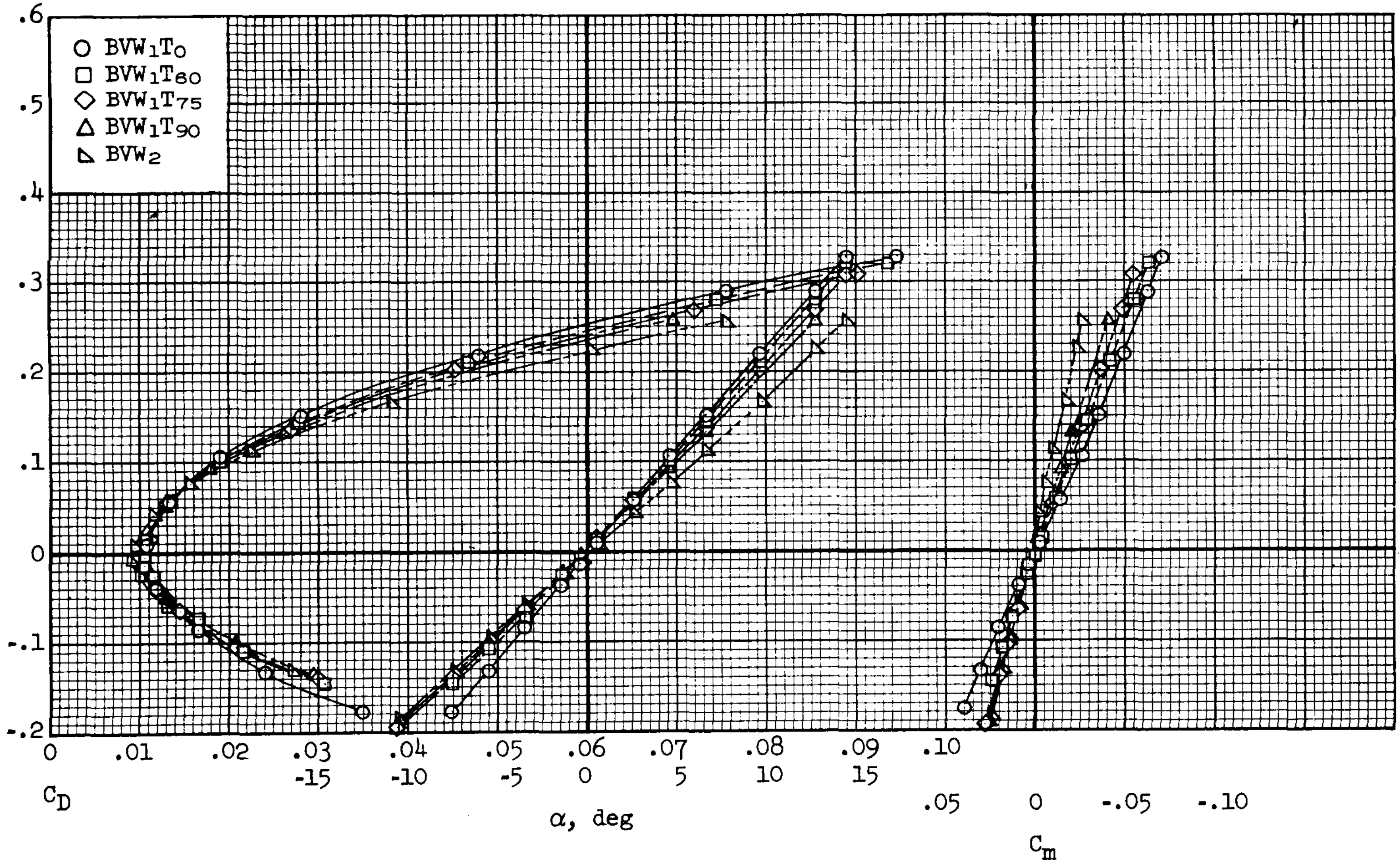
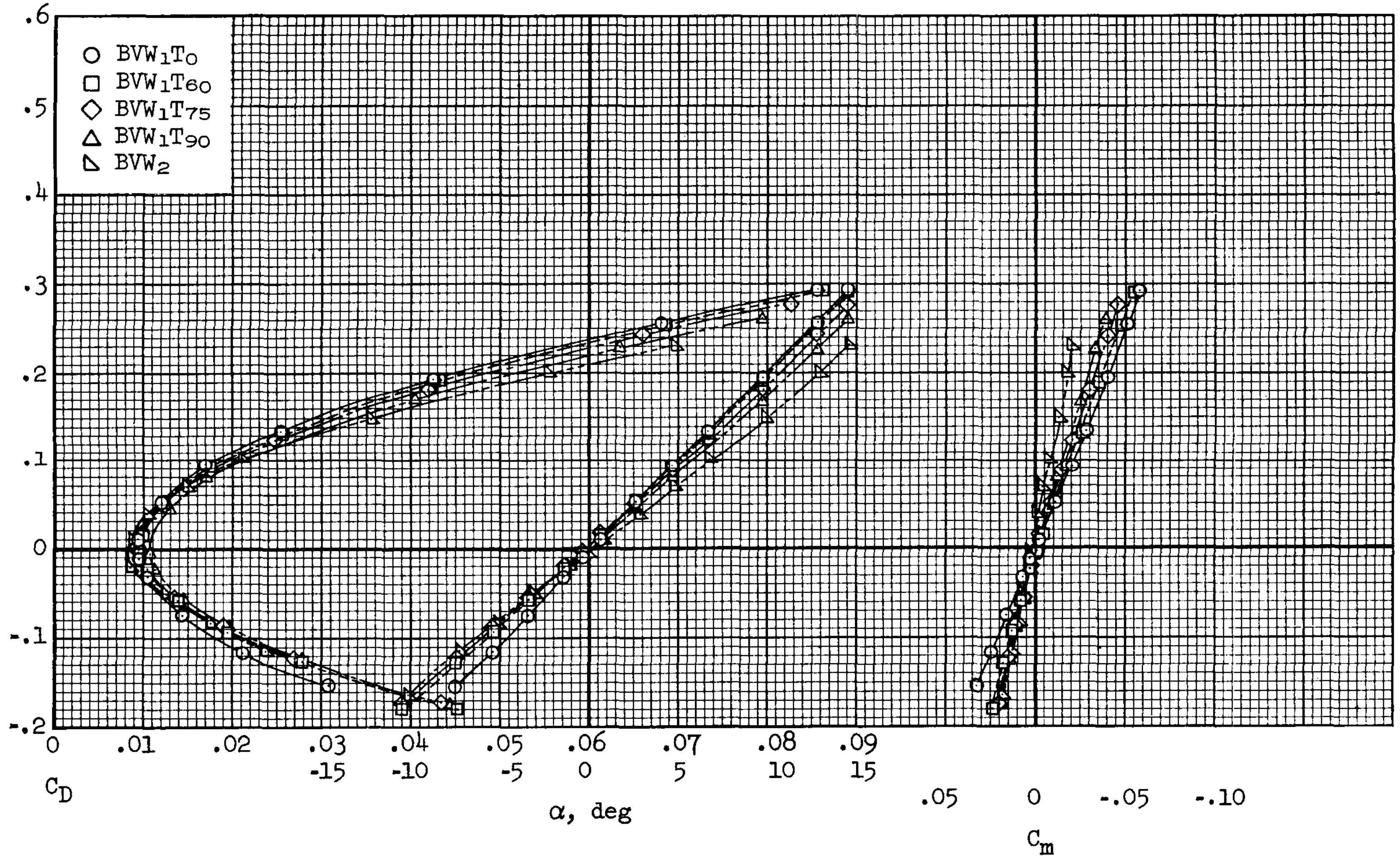
(f) M = 2.49

Figure 2.- Continued.



(g) M = 3.06

Figure 2.- Continued.



(h) M = 3.54

Figure 2.- Concluded.

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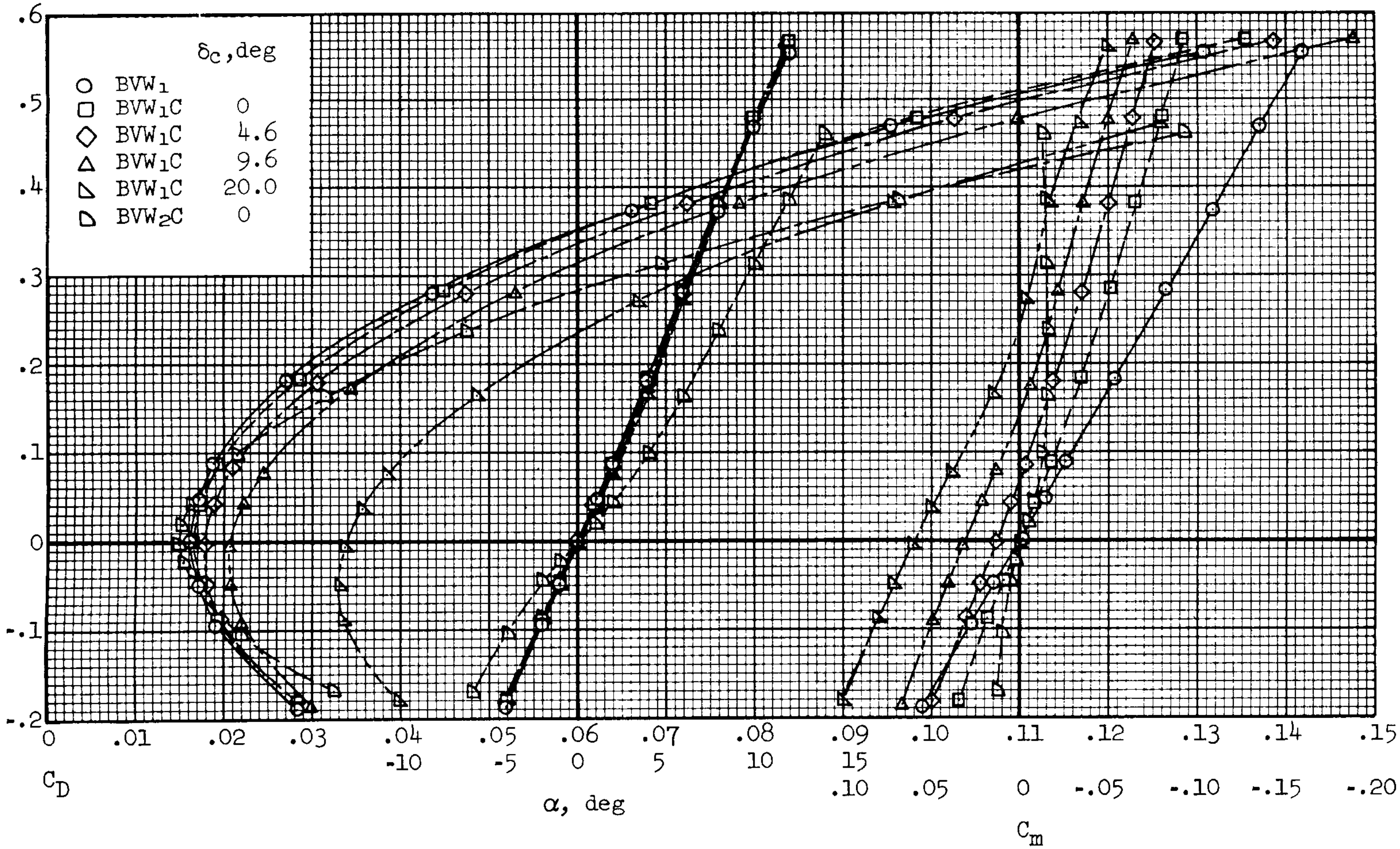

(a) M = 1.30

Figure 3.- Effect of a canard surface on the longitudinal aerodynamic characteristics; tips undeflected or removed.

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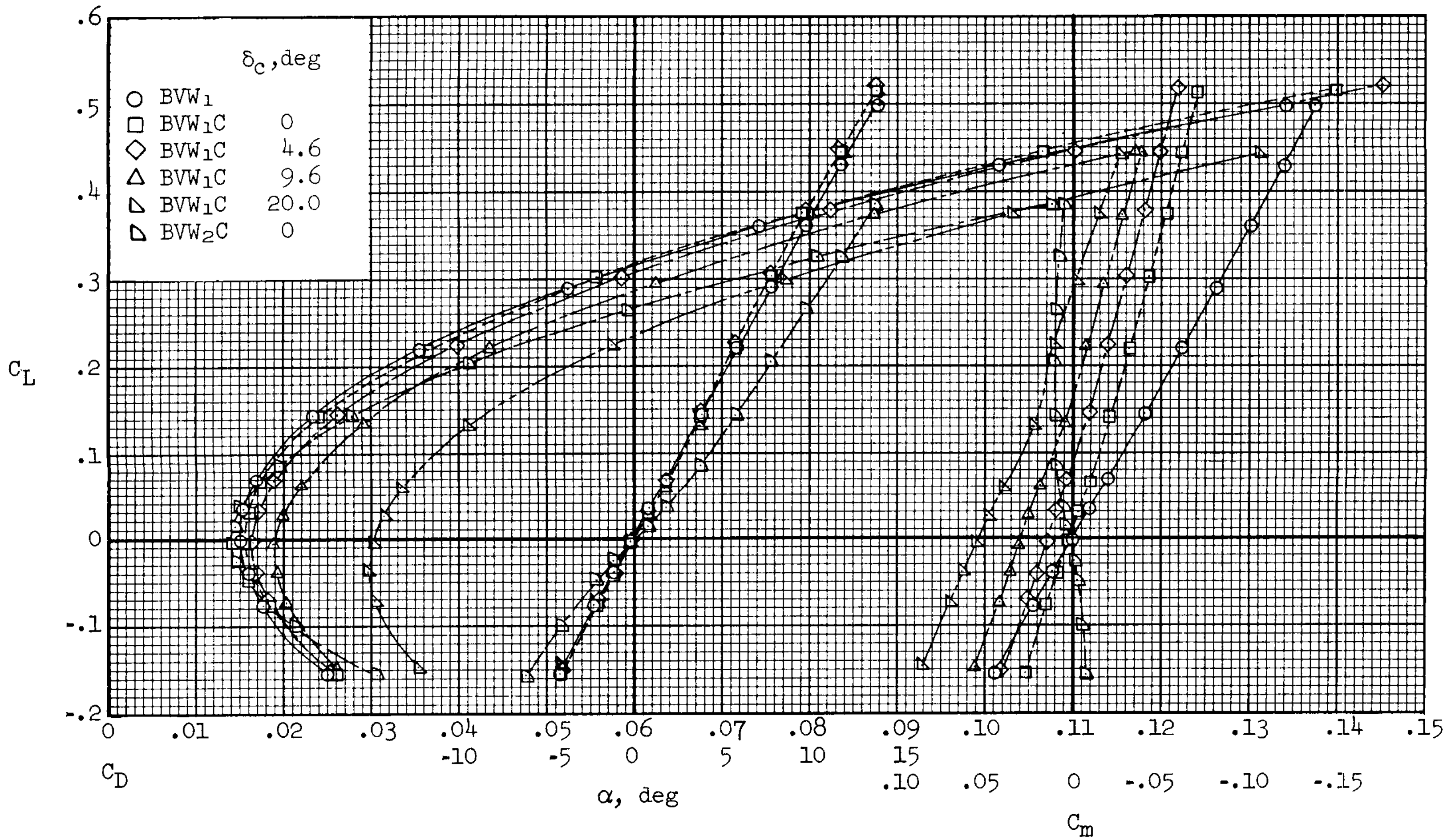

(b) M = 1.70

Figure 3.- Continued.

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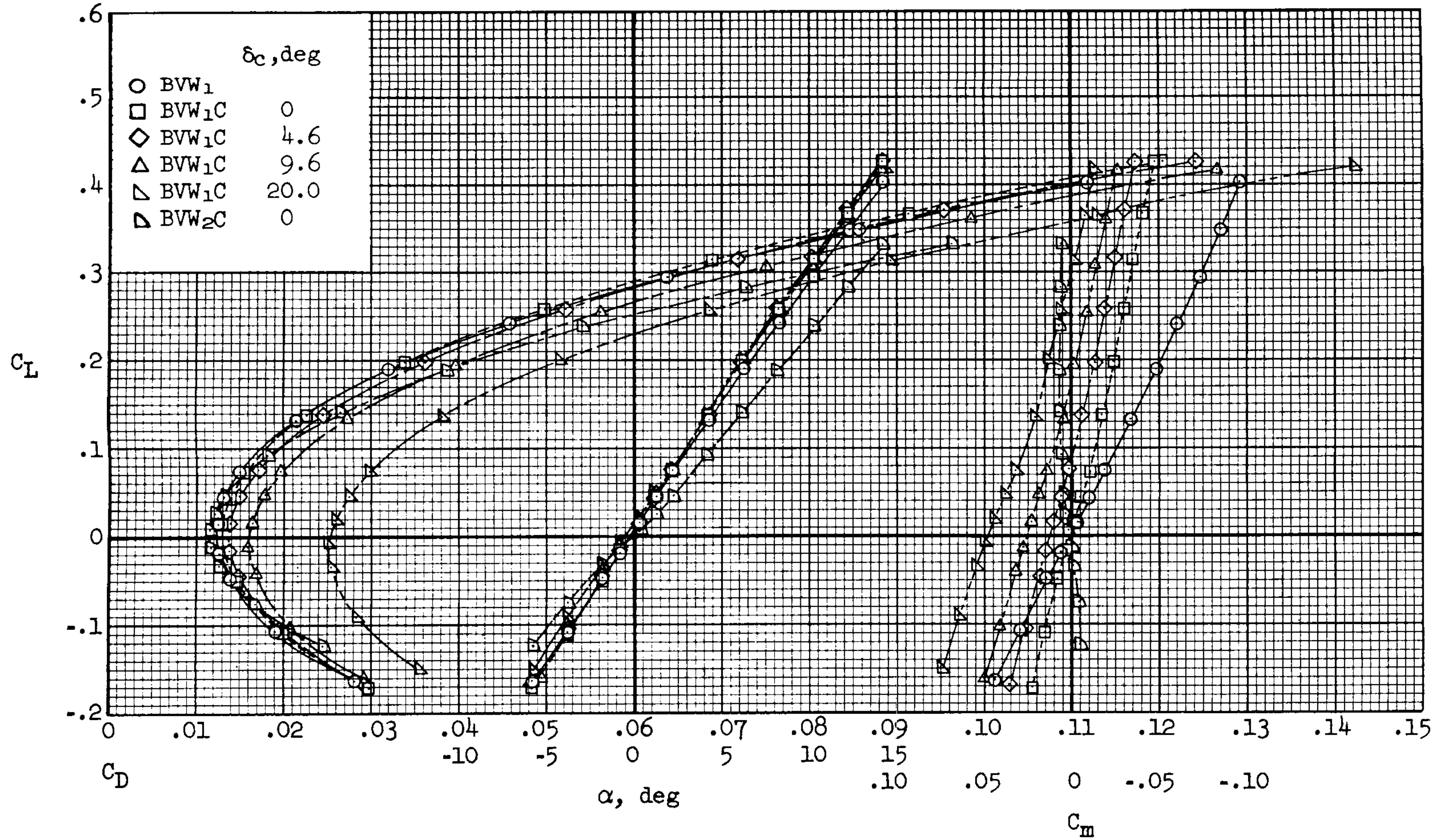

(c) M = 2.22

Figure 3.- Concluded.

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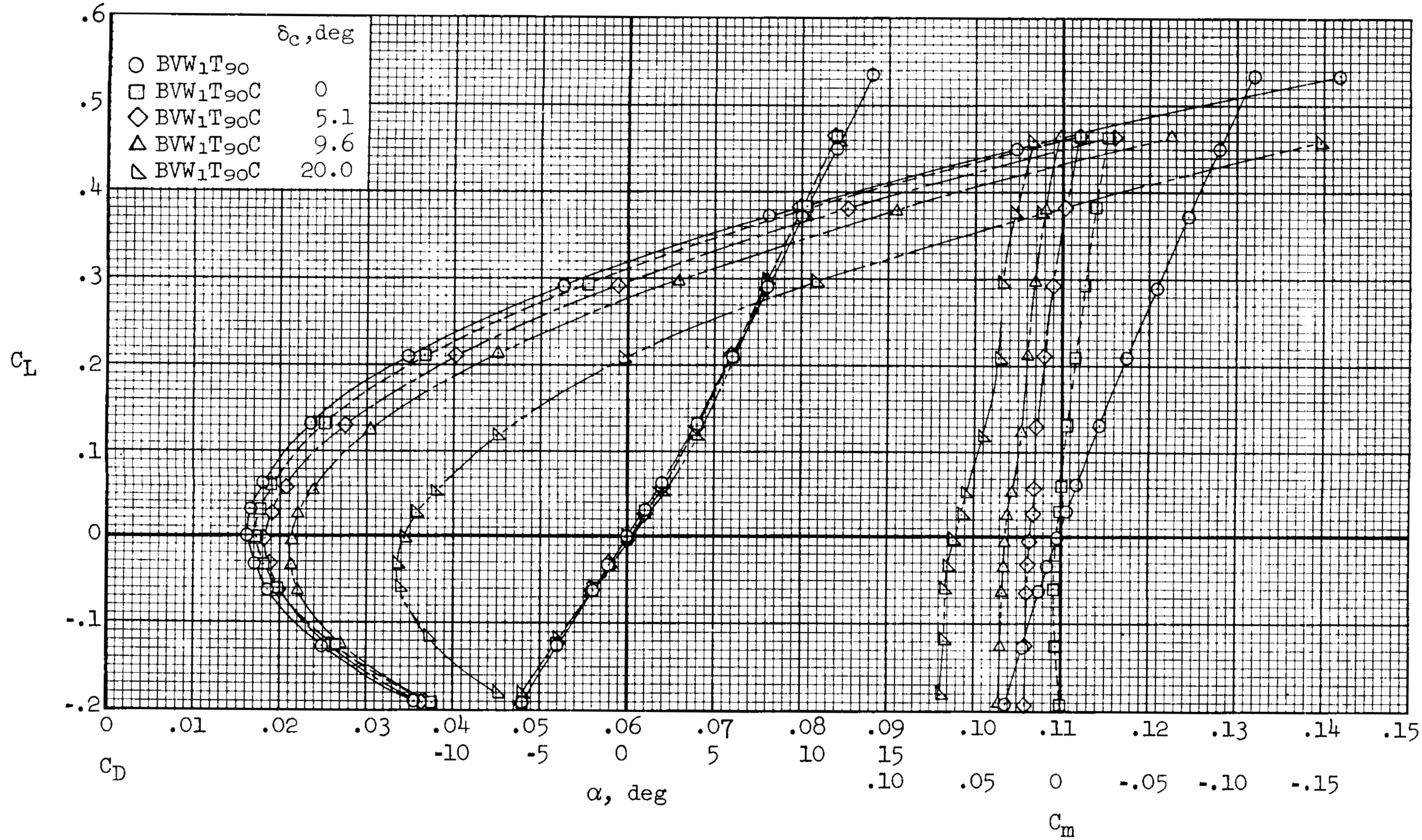

(a) M = 1.30

Figure 4.- Effect of a canard surface on the longitudinal aerodynamic characteristics; tips deflected 90°.

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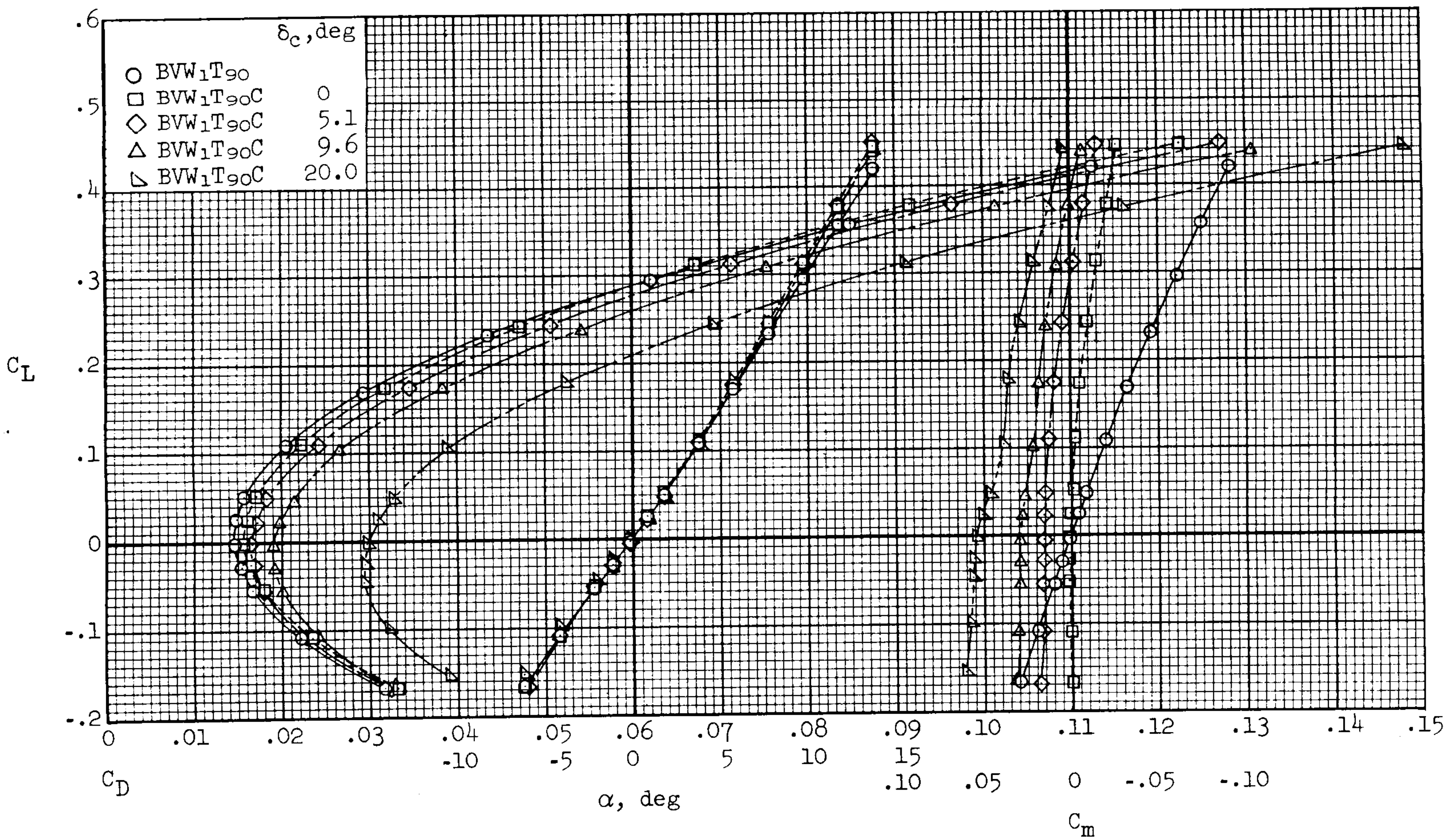

(b) M = 1.70

Figure 4.- Continued.

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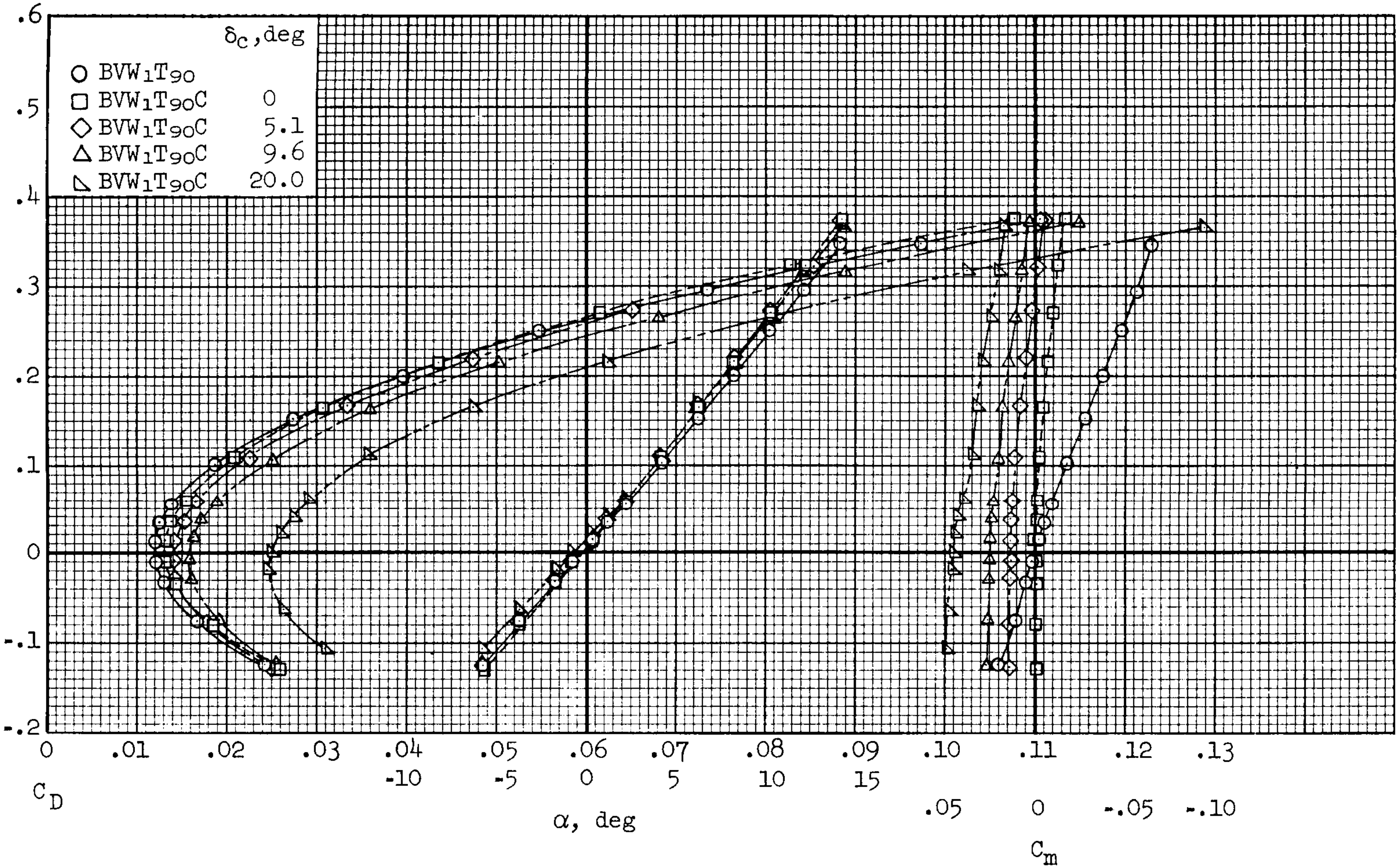

(c) M = 2.22

Figure 4.- Concluded.

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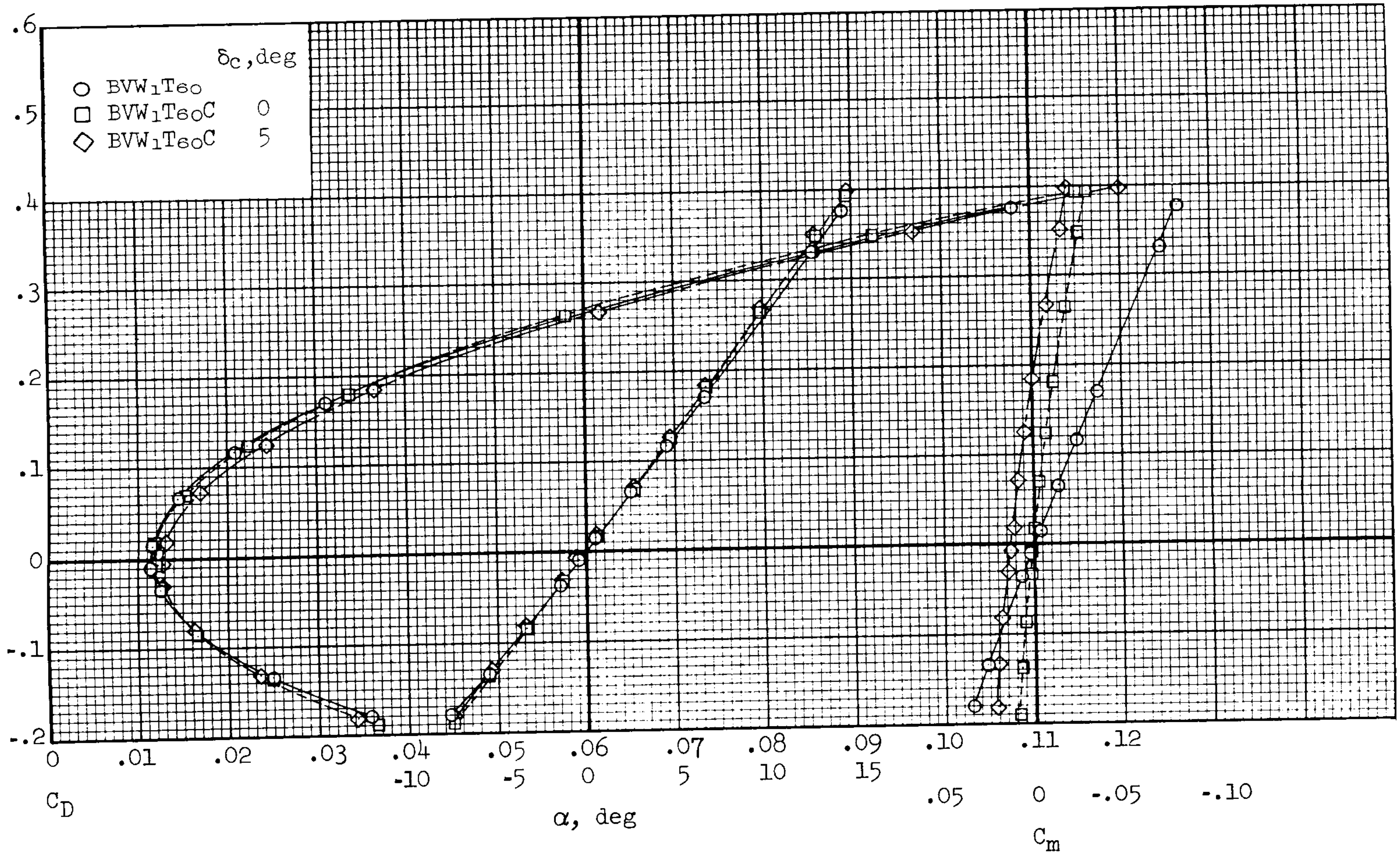

(a) M = 2.49

Figure 5.- Effect of a canard surface on the longitudinal aerodynamic characteristics; tips deflected 60°.

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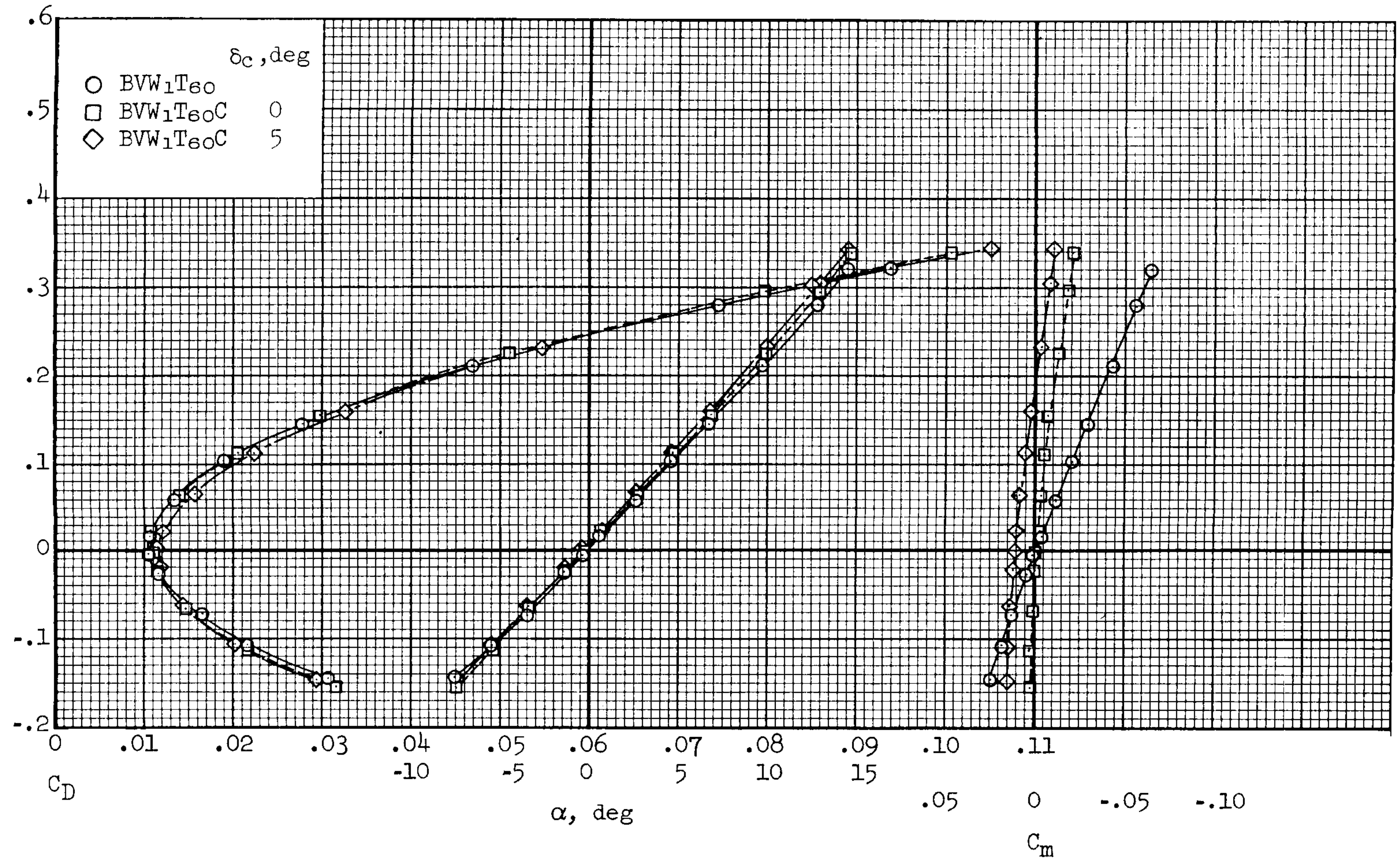

(b) M = 3.06

Figure 5.- Continued.

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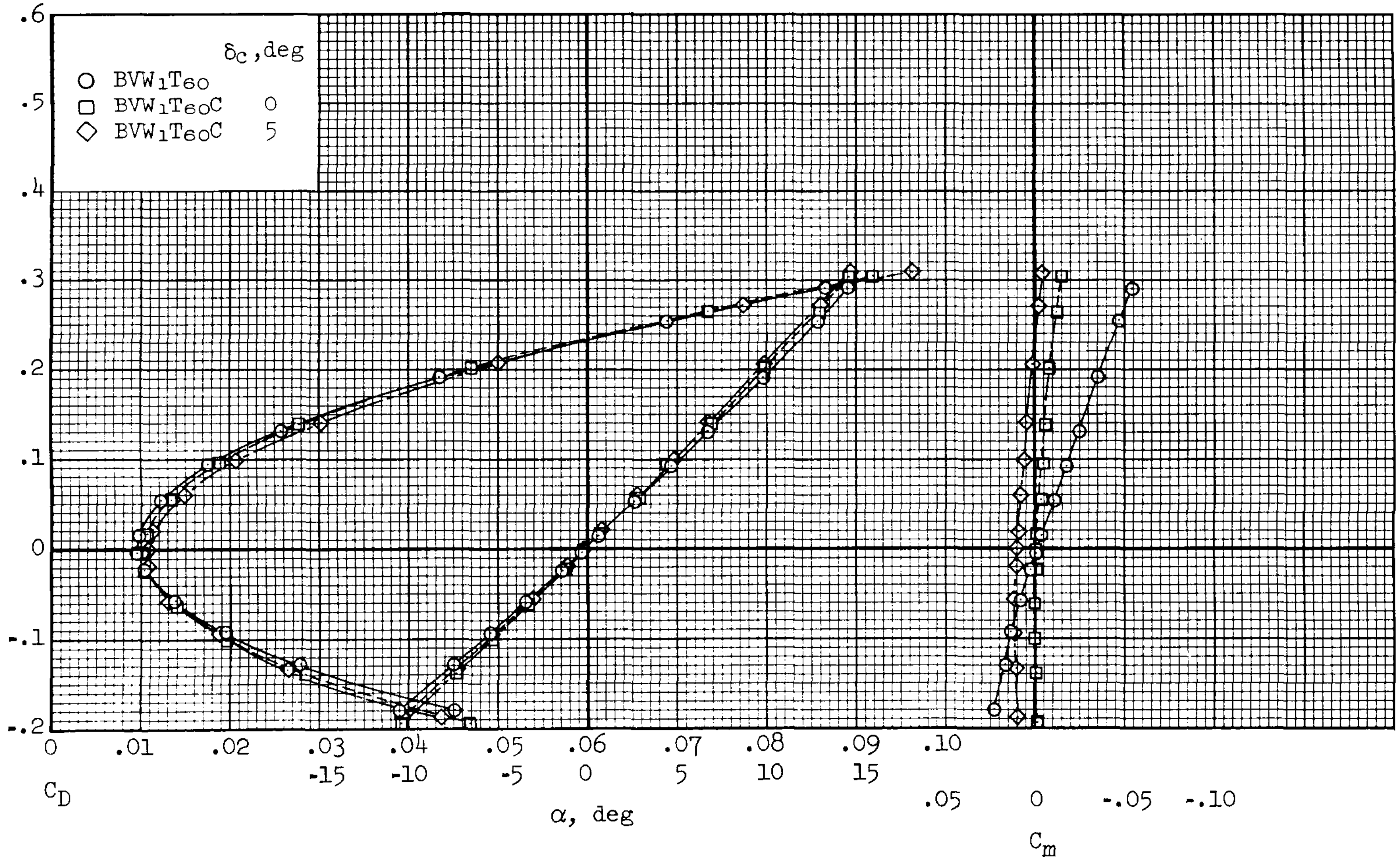

(c) M = 3.54

Figure 5.- Concluded.

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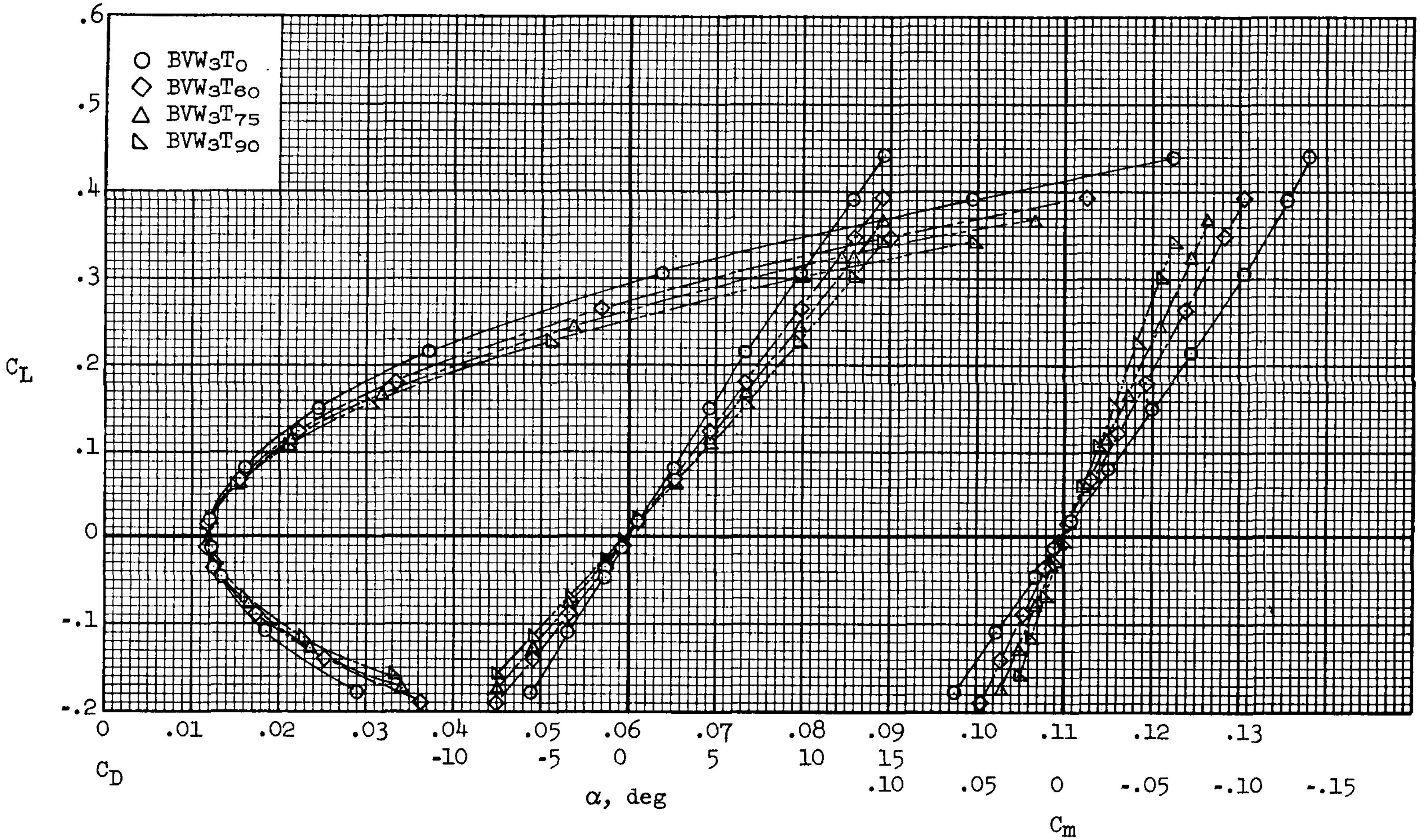
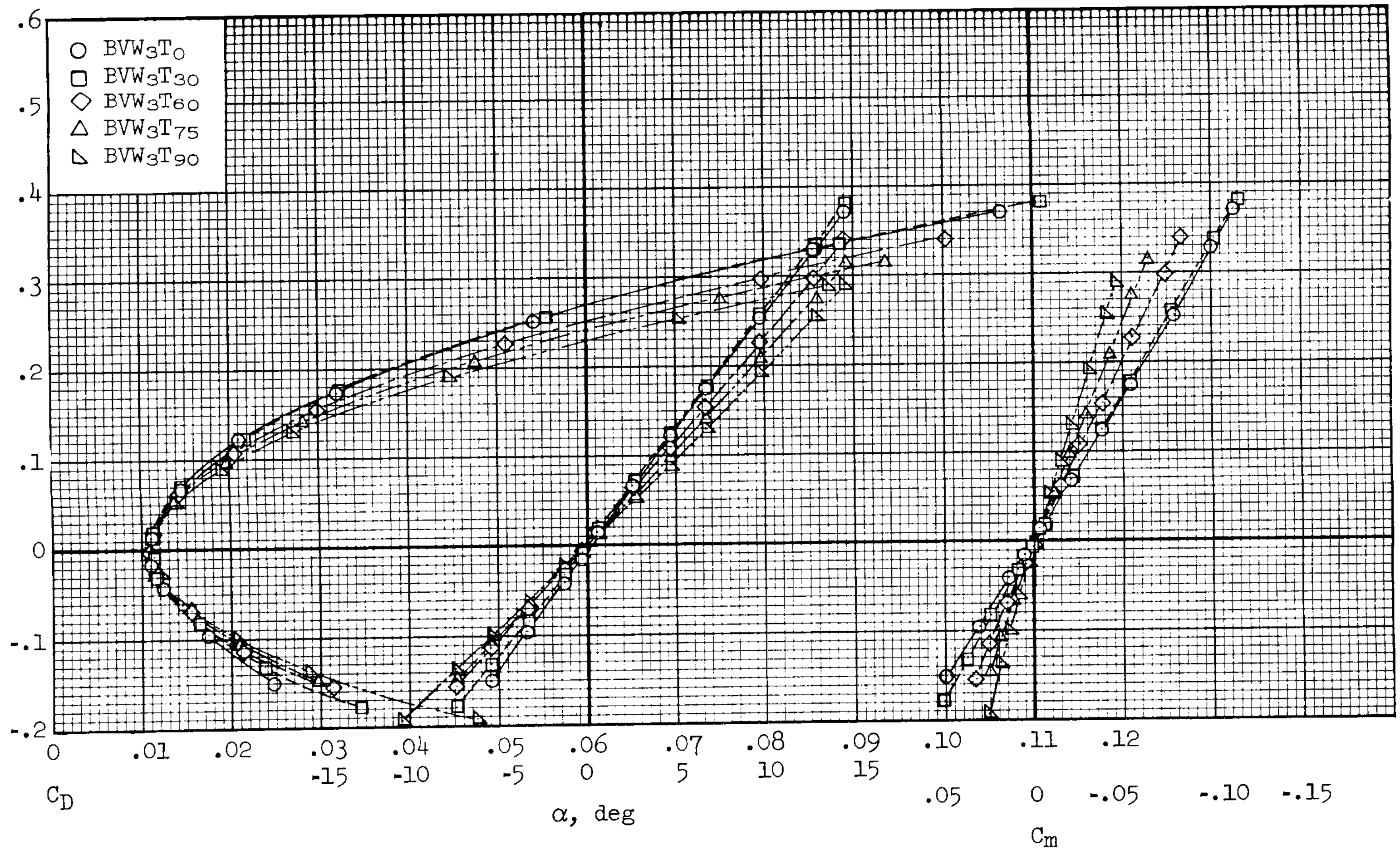


(a) M = 2.49

Figure 6.- Effect of various wing tip deflections on the longitudinal aerodynamic characteristics of the model with sweptback wing tips; canard off.



(b) M = 3.06

Figure 6.- Continued.

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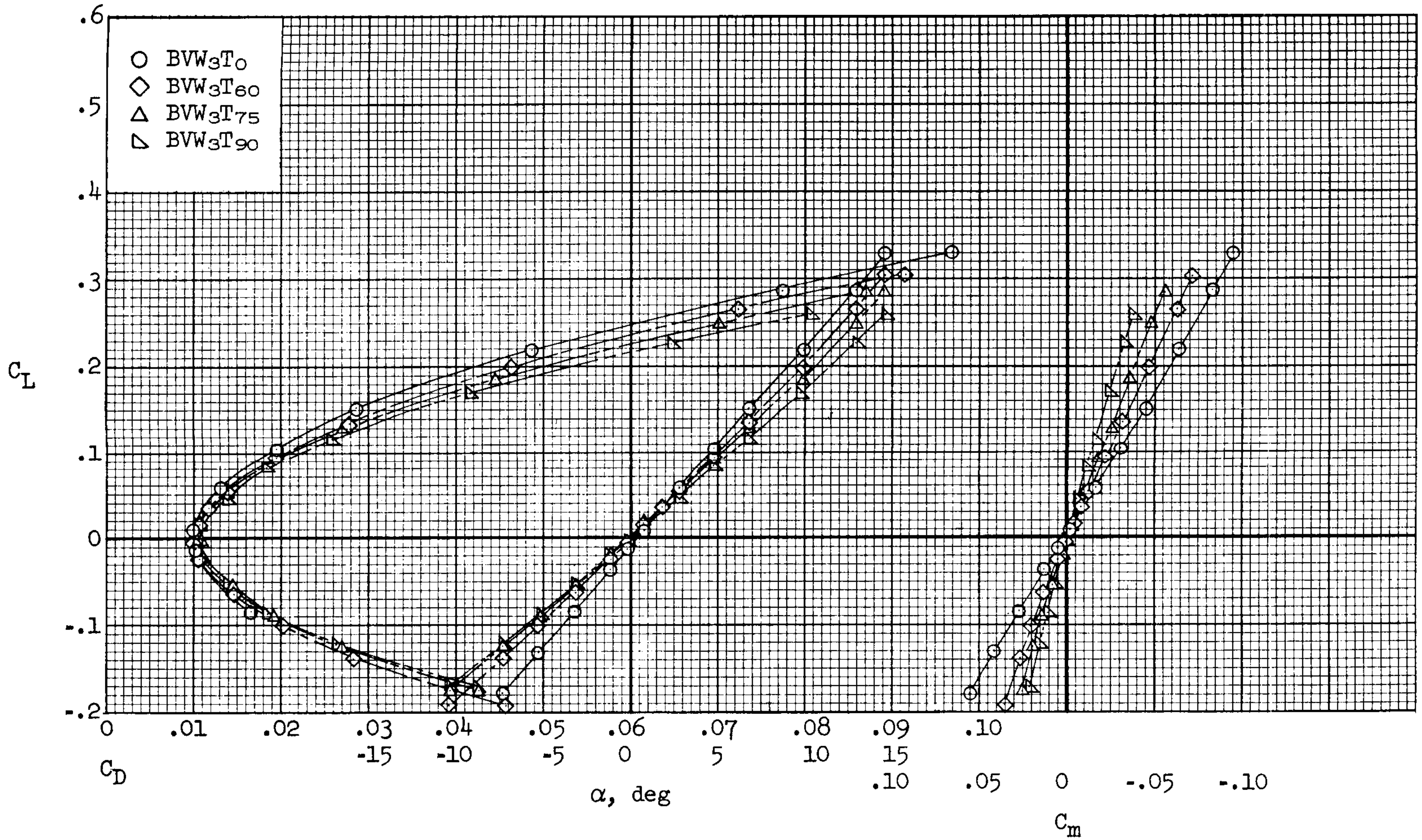

(c) M = 3.54

Figure 6.- Concluded.

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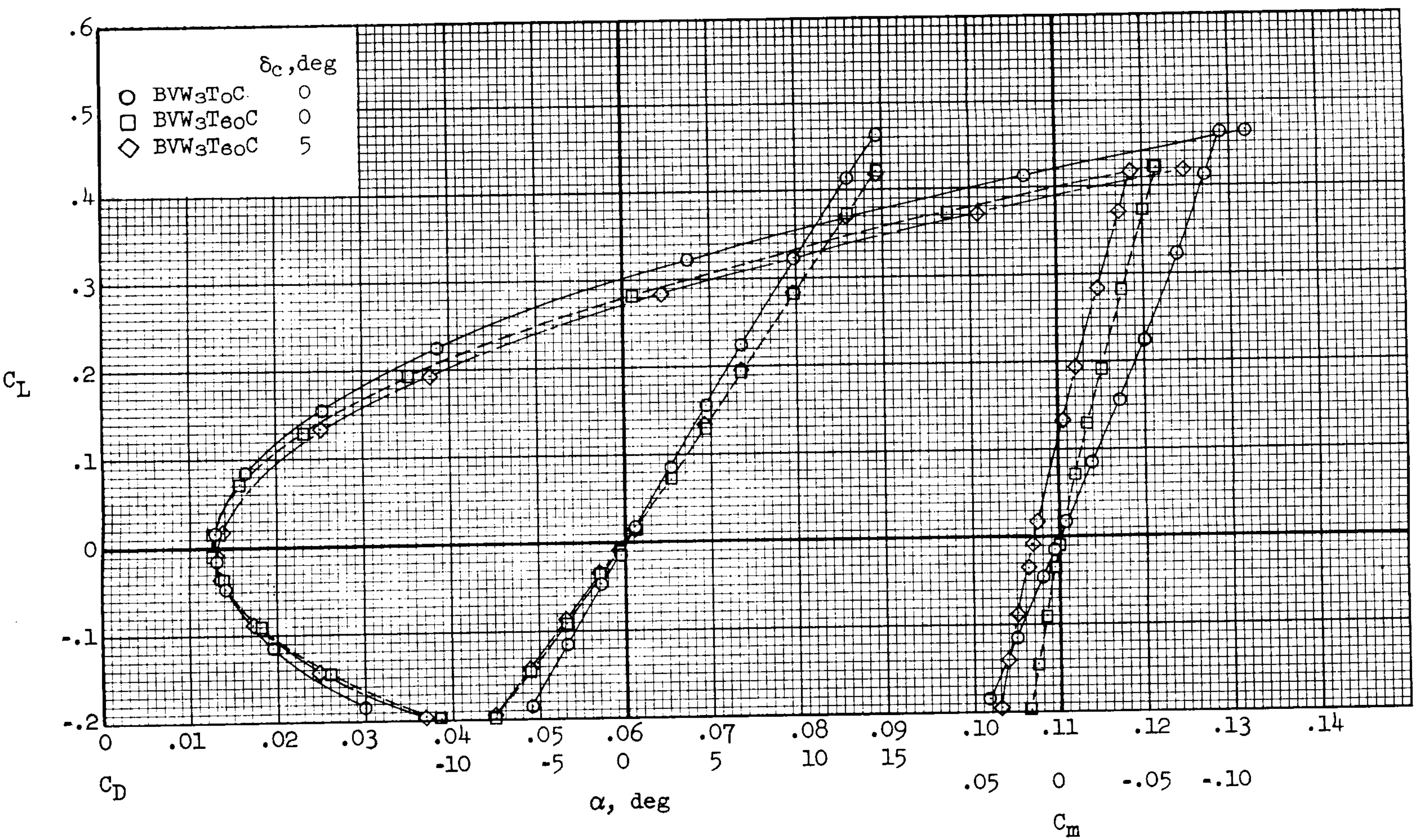

(a) M = 2.49

Figure 7.- Effect of combination of canard surface and wing tip deflection on the longitudinal aerodynamic characteristics of the model with sweptback wing tips.

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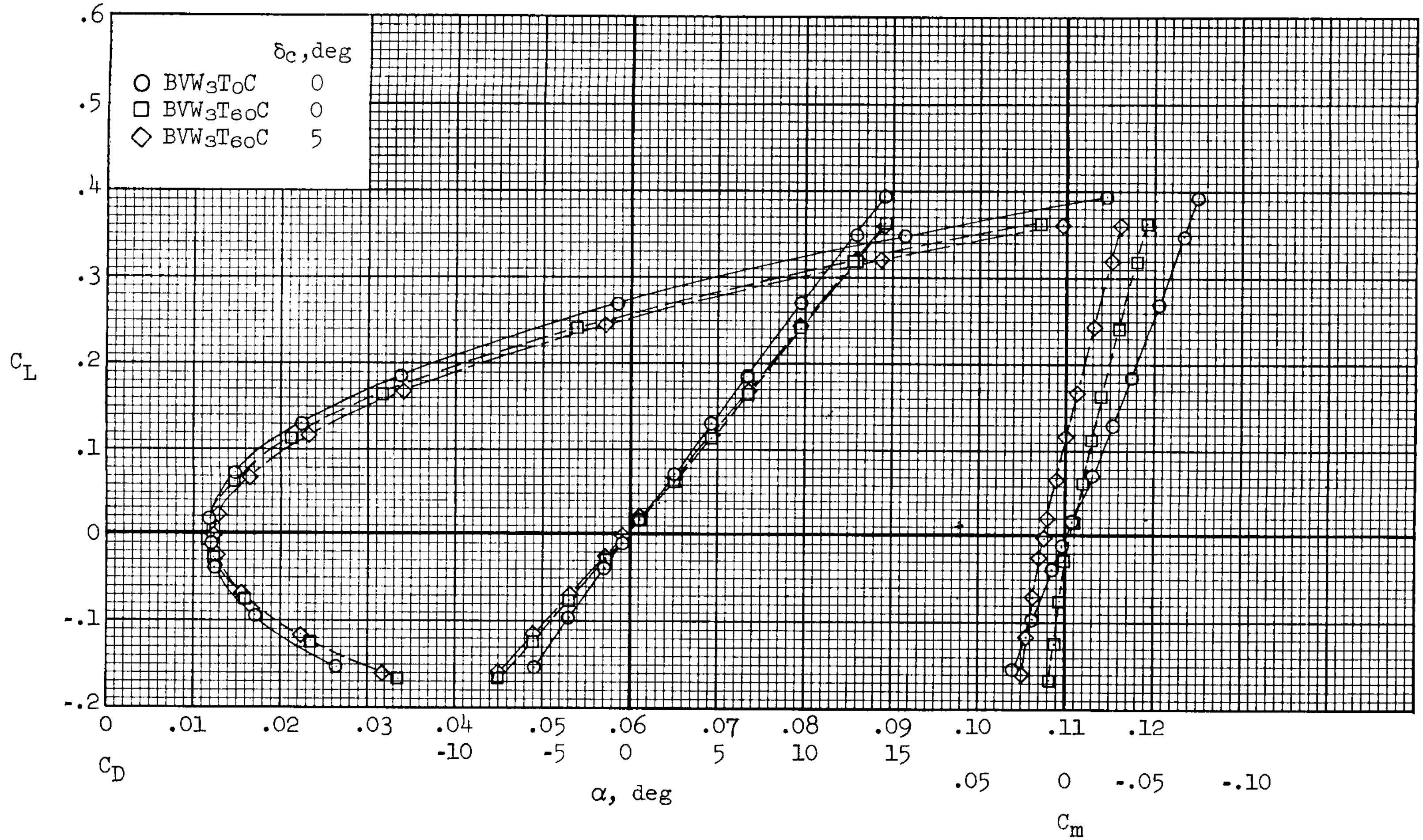

(b) $M = 3.06$

Figure 7.- Continued.

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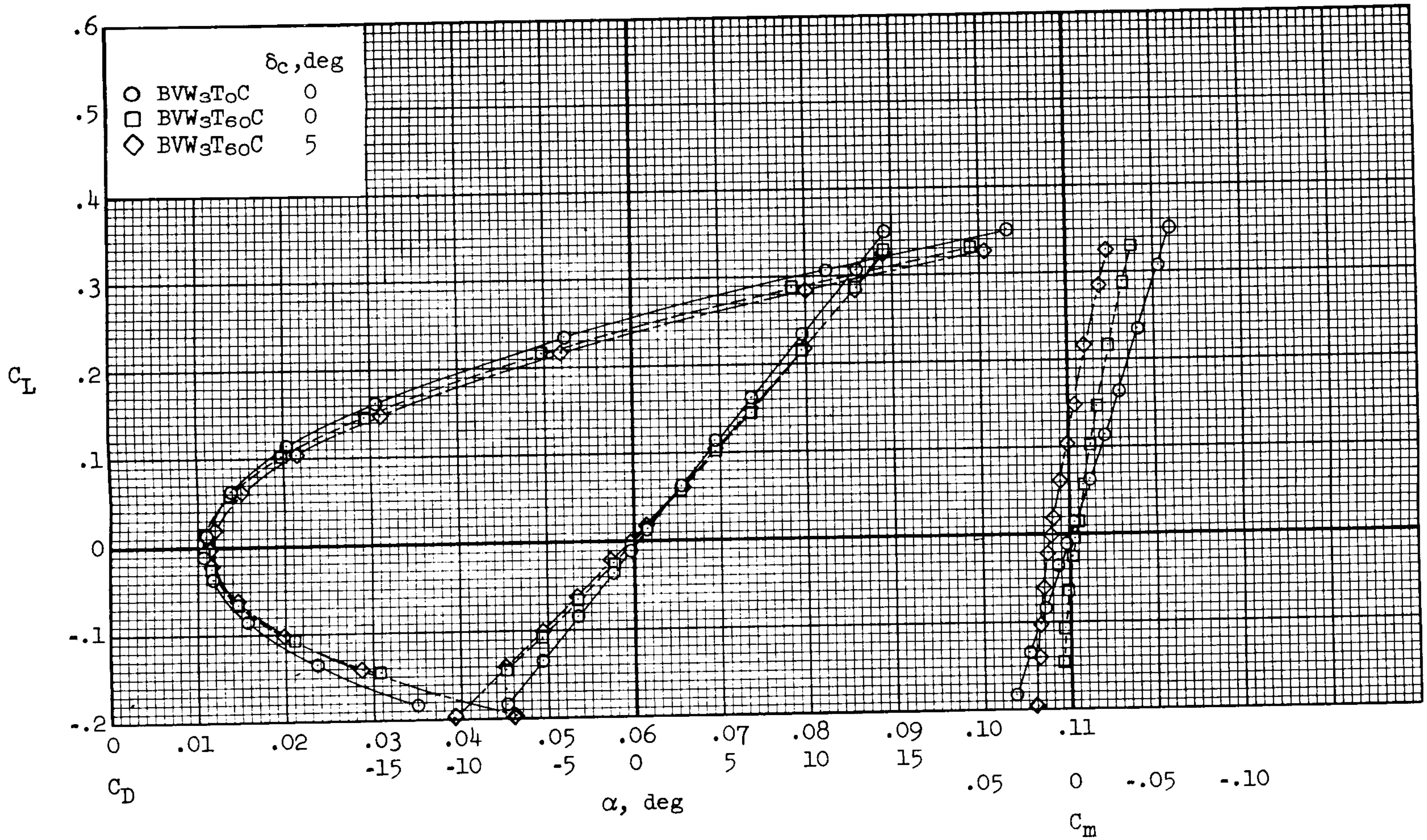

(c) M = 3.54

Figure 7.- Concluded.

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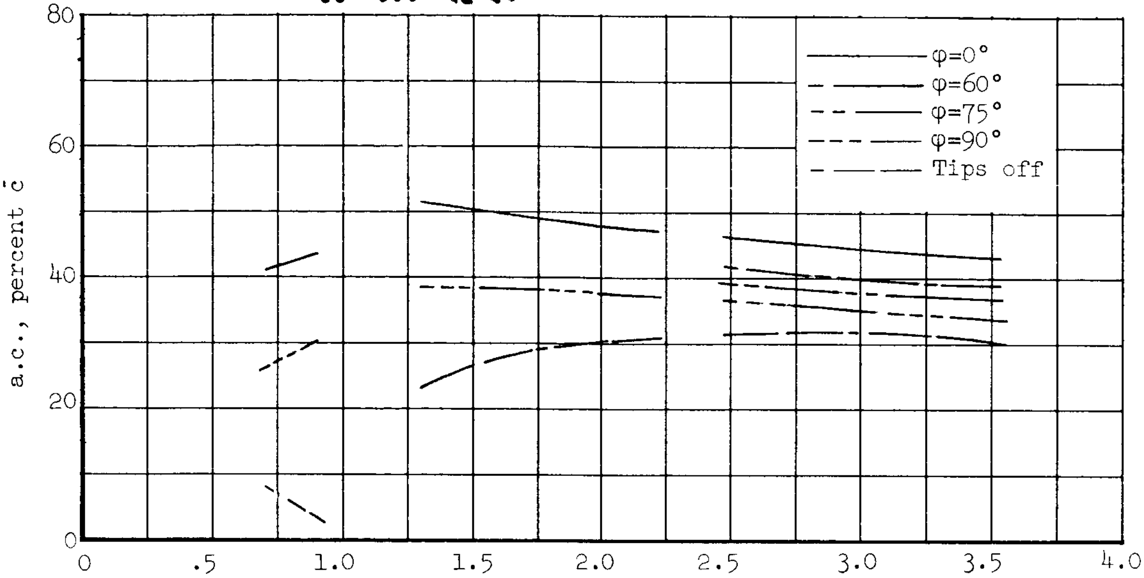
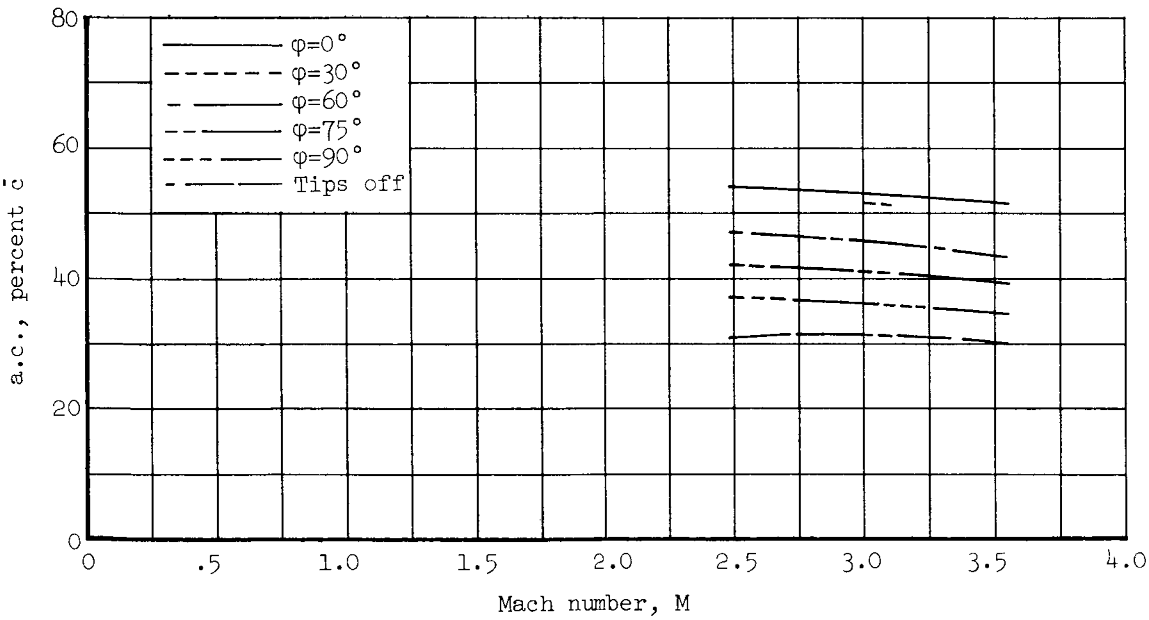


(a) Triangular tips



(b) Swept tips

Figure 8.- Variation with Mach number of the effects of tip deflection or tip removal on the aerodynamic-center location with the canard off.

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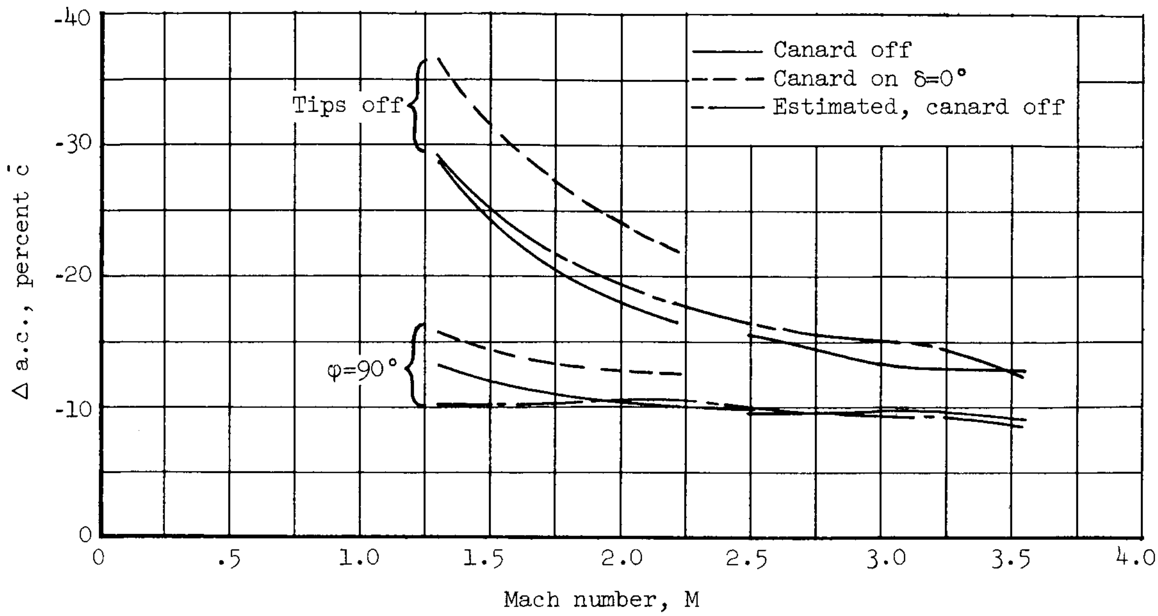
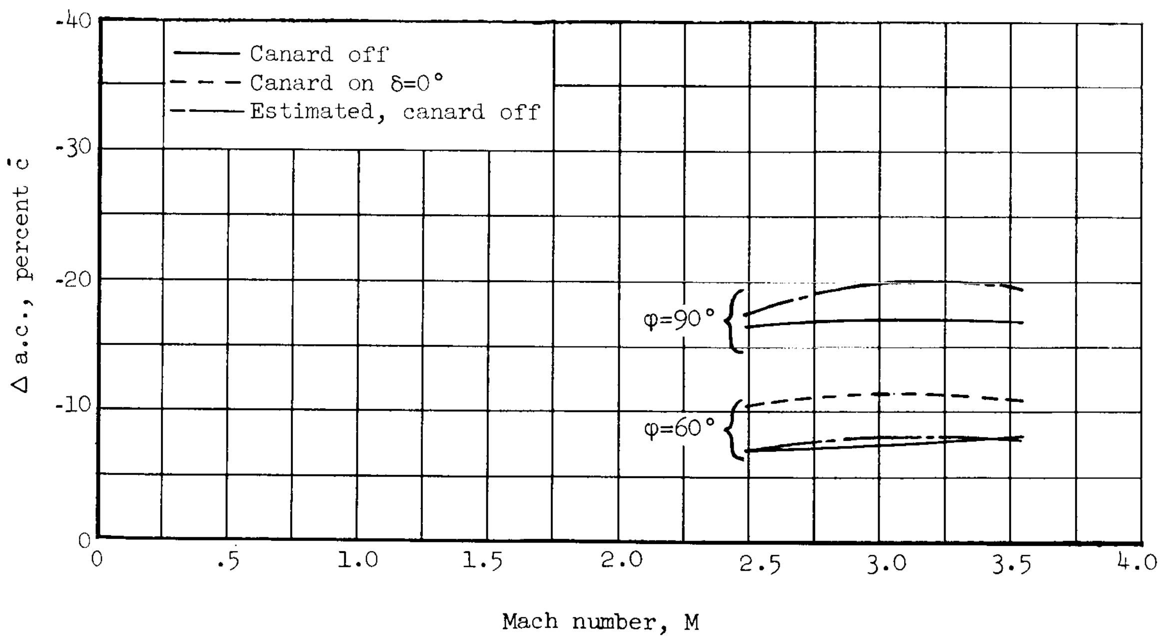
[redacted]



(a) Triangular tips



(b) Swept tips

Figure 9.- Variations of forward aerodynamic-center shifts with Mach number resulting from deflecting or removing the tips with canard off and on.

[redacted]

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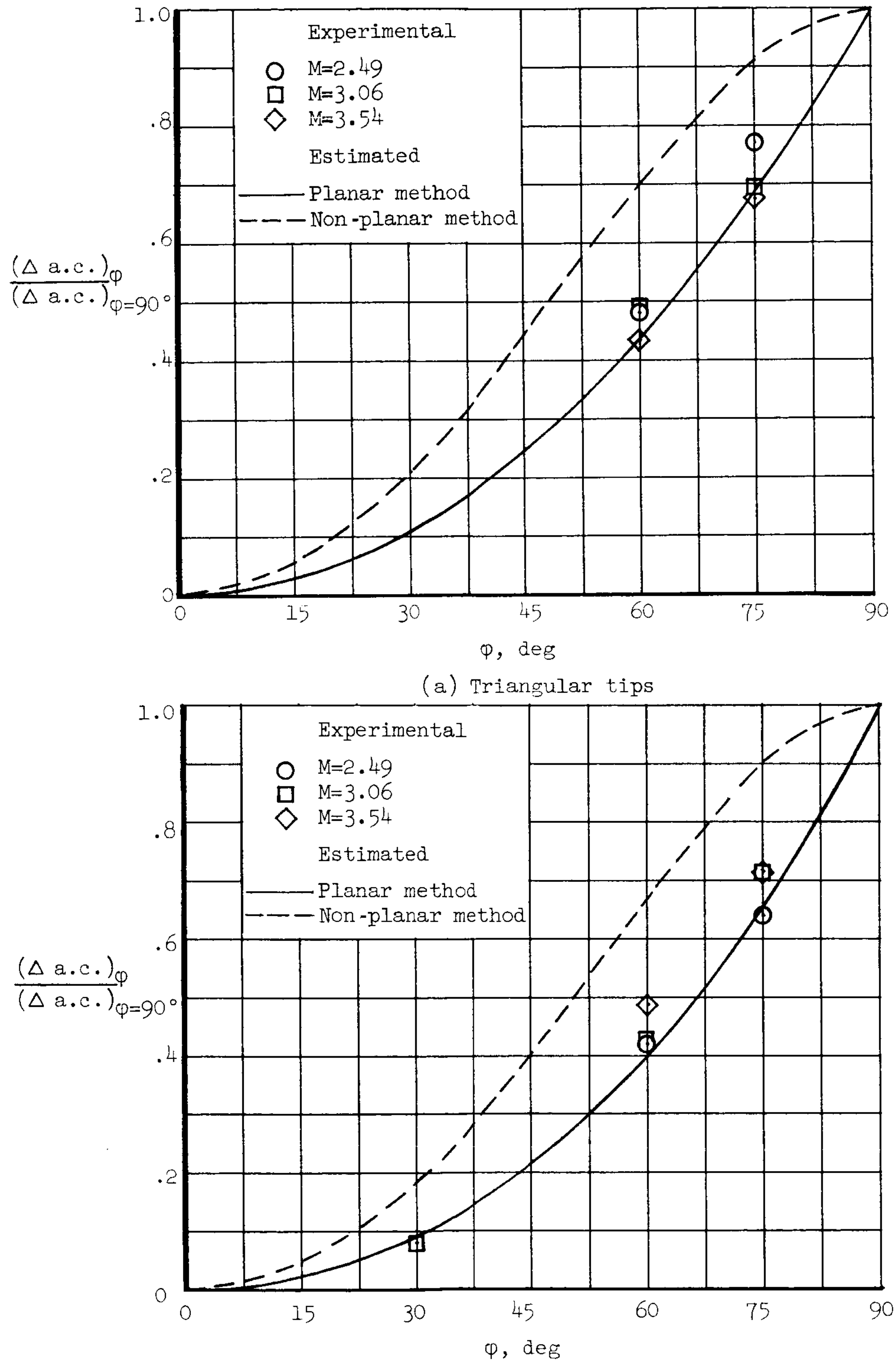

(b) Swept tips

Figure 10.- Variation of aerodynamic-center movement with tip deflection with the canard off.

[redacted]

[redacted]

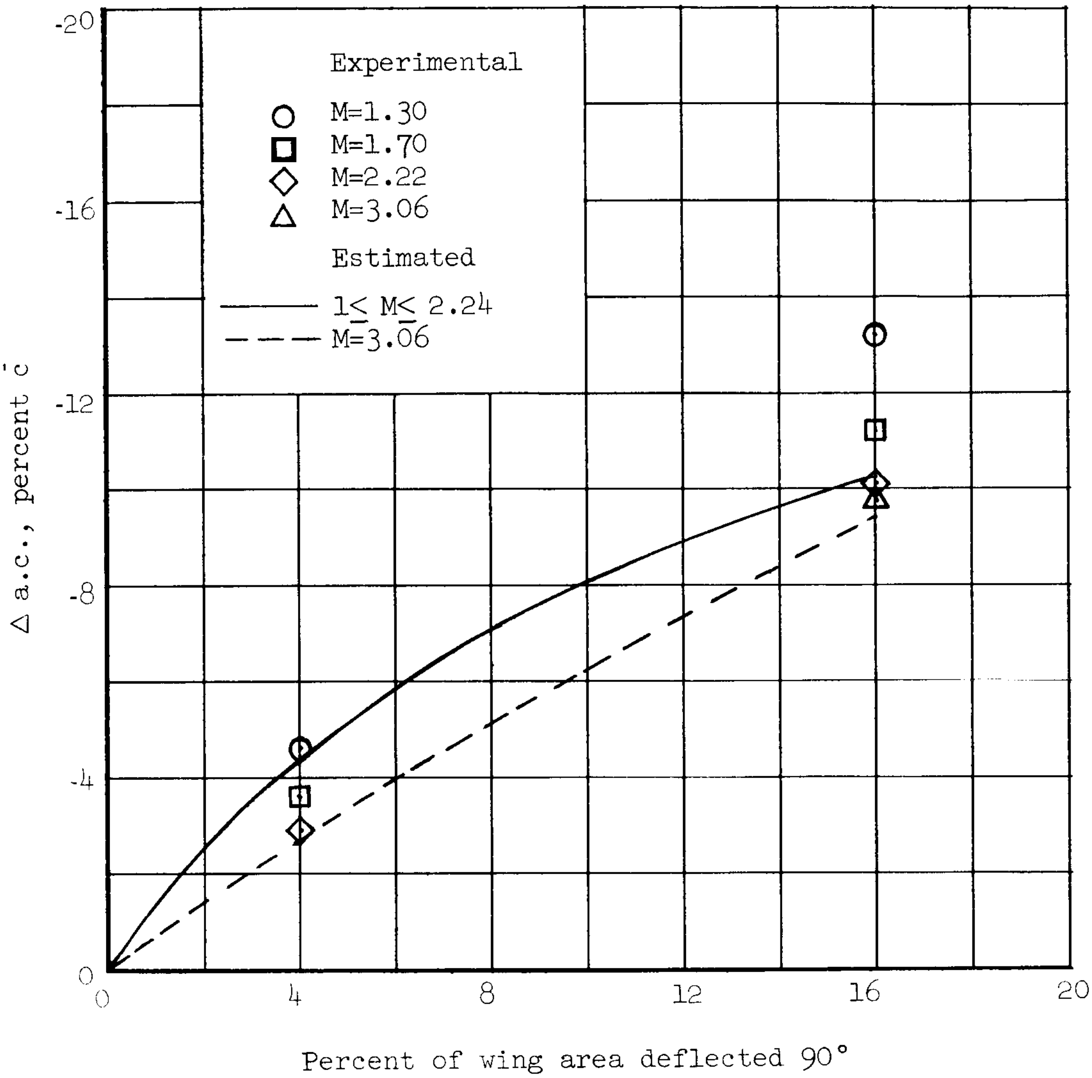

Figure 11.- Effect of amount of area deflected 90° on the forward aerodynamic-center shifts for triangular tips configurations with no canard.

[redacted]

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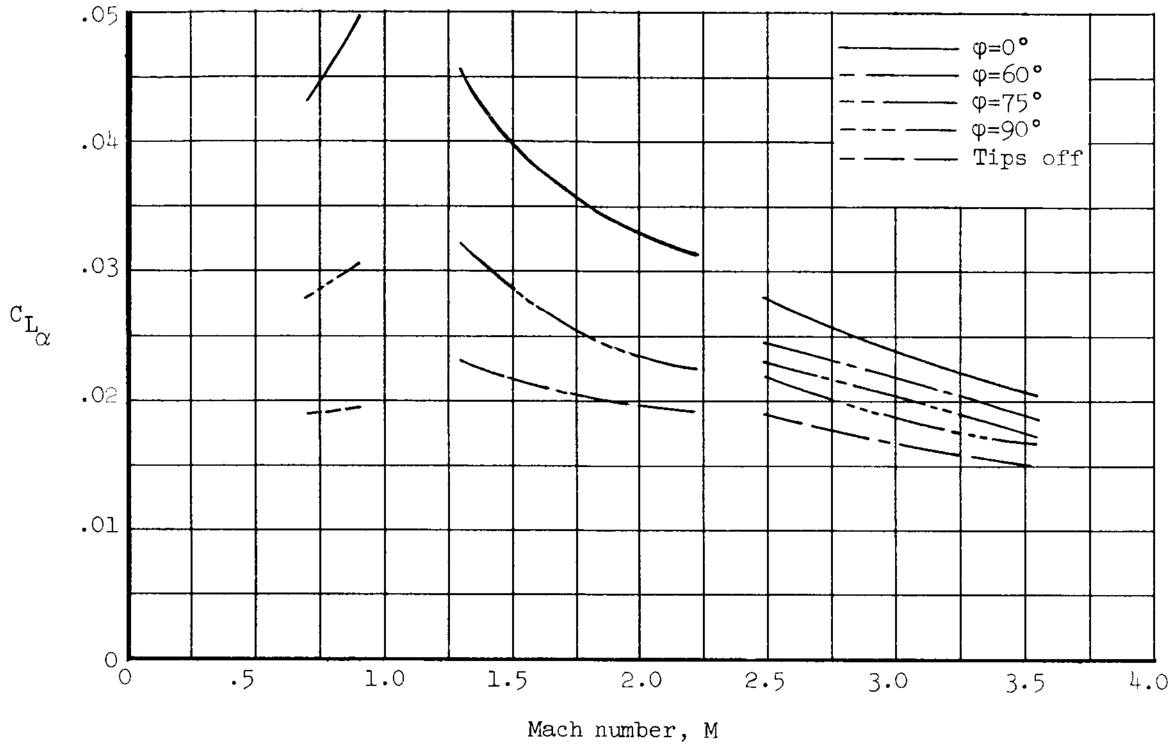
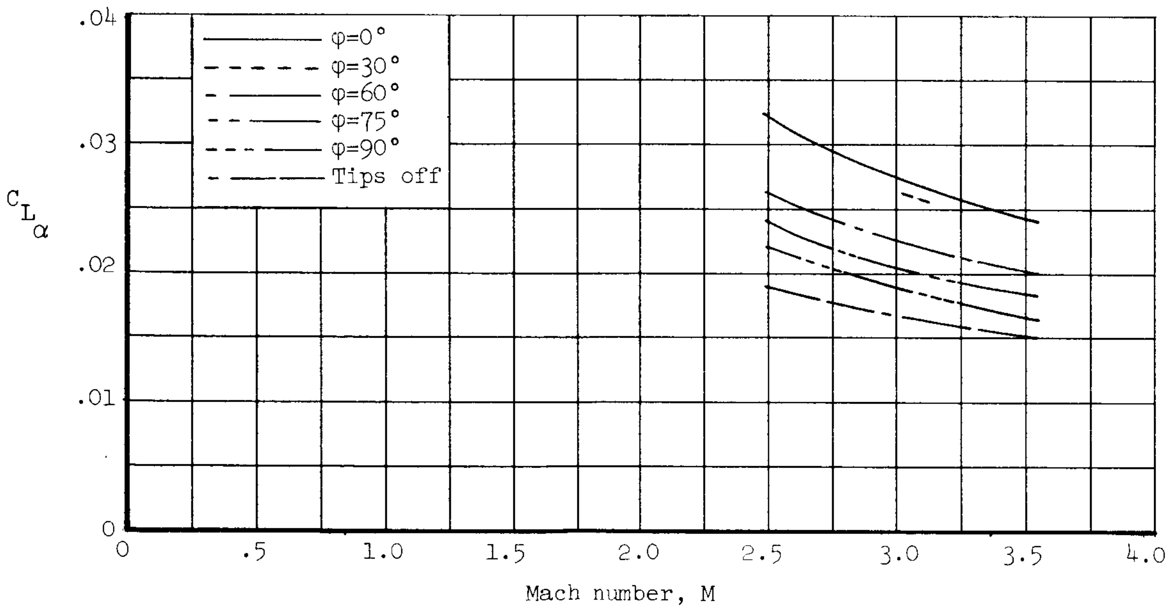
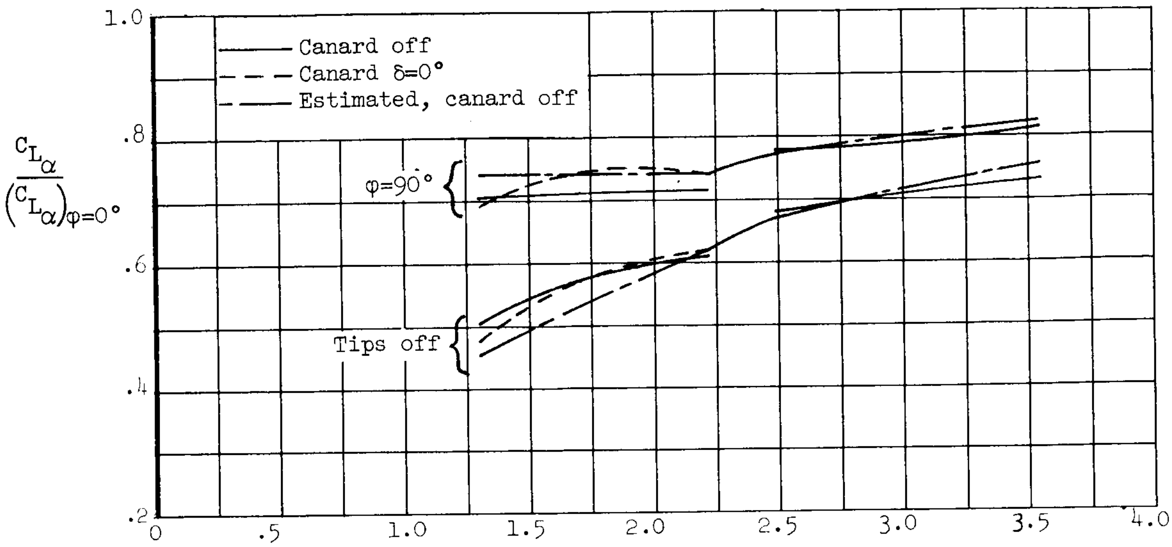


(a) Triangular tips

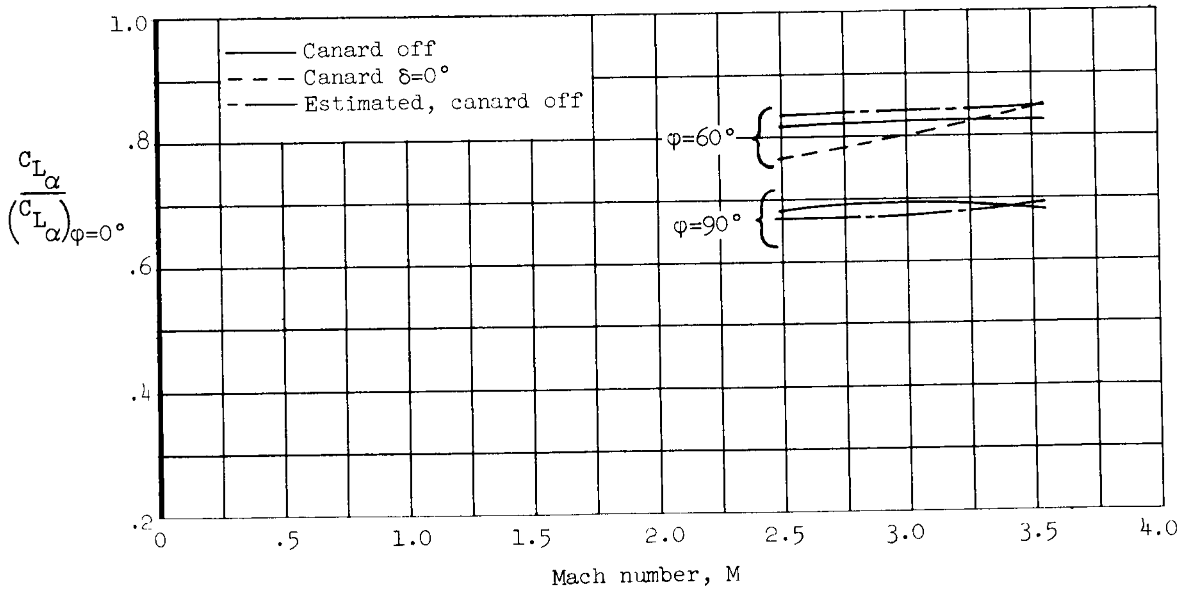


(b) Swept tips

Figure 12.- Variation with Mach number of the effects of tip deflection or tip removal on the lift-curve slope with the canard off.



(a) Triangular tips



(b) Swept tips

Figure 13.- Variations with Mach number of the effects on the lift-curve slope resulting from deflecting or removing the tips with the canard off and on.

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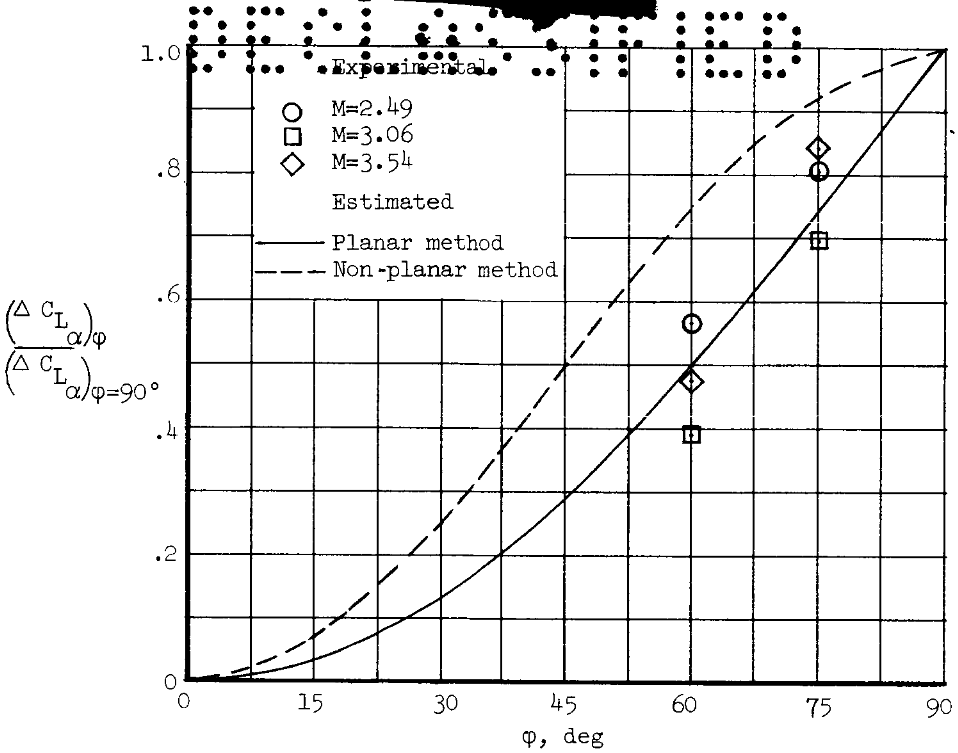
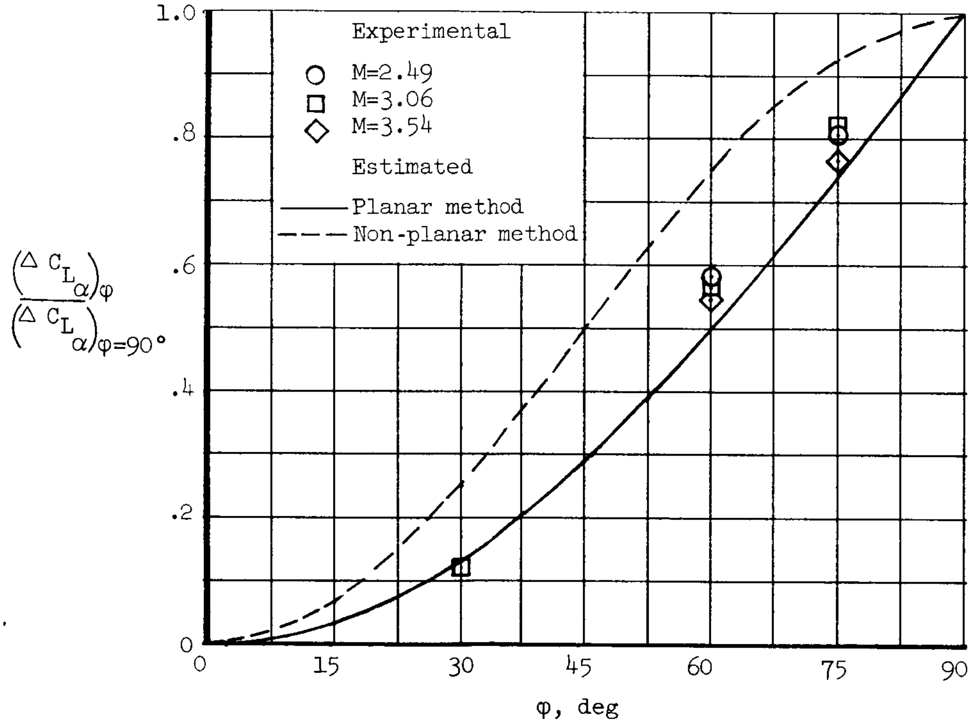


(a) Triangular tips



(b) Swept tips

Figure 14.- Variation of lift-curve slope ratio with tip deflection with the canard off.

[redacted]

[redacted]

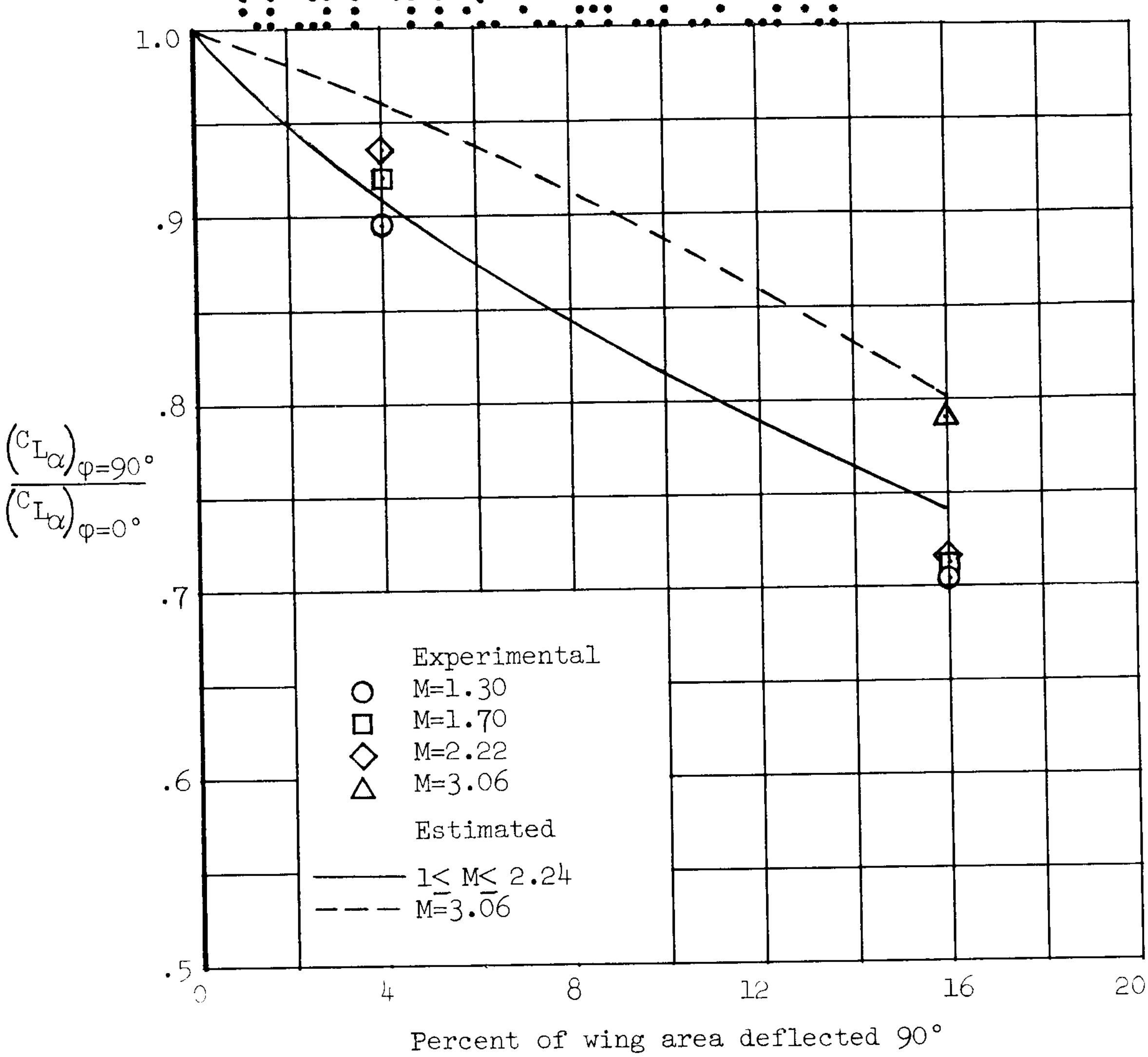


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Figure 15.- Effect of amount of area deflected 90° on the lift-curve slope ratio for triangular tips configurations with no canard.

[redacted]

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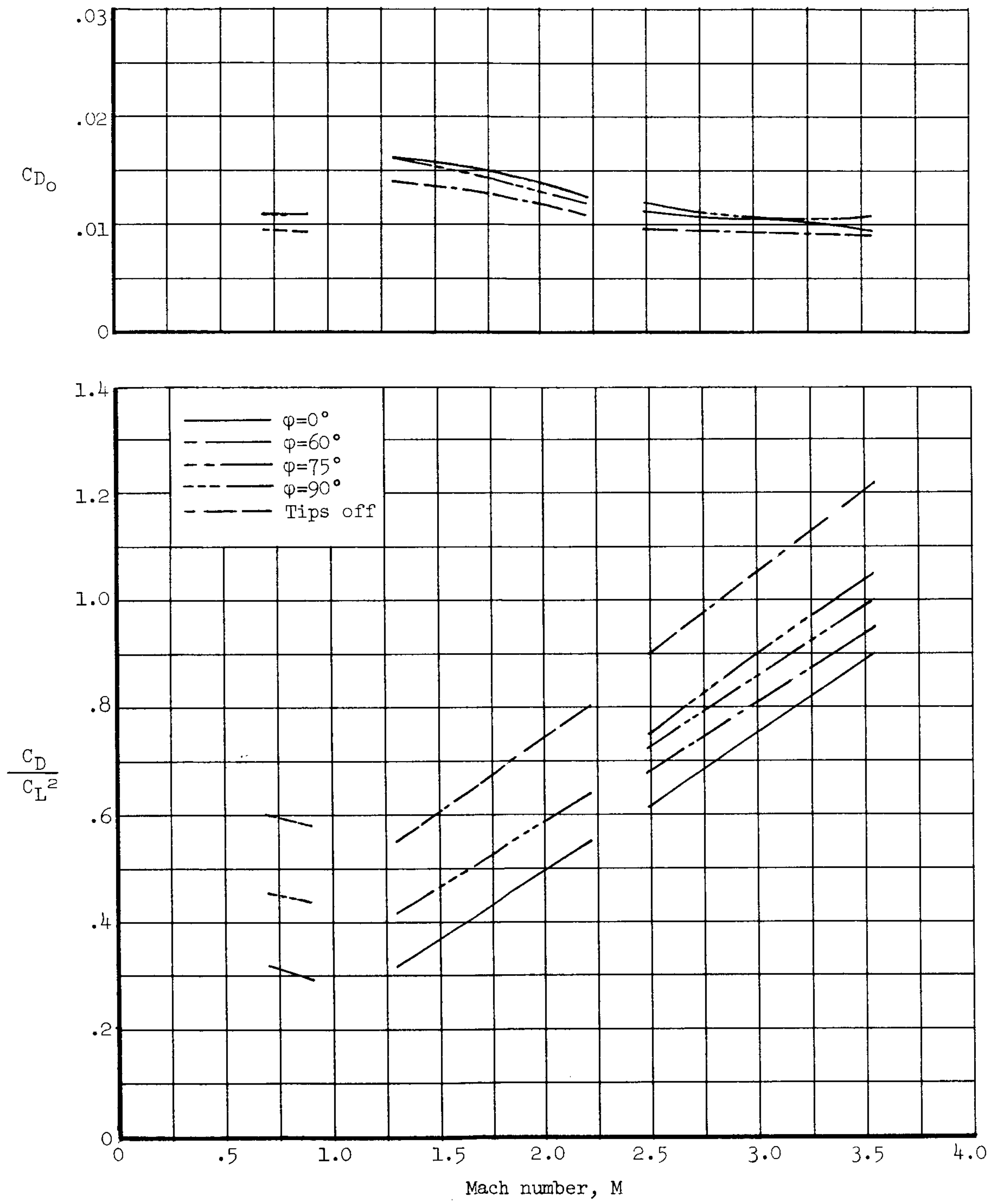

(a) Triangular tips

Figure 16.- Variation with Mach number of the effects of tip deflection or tip removal on the drag at zero lift and drag-due-to-lift with the canard off.

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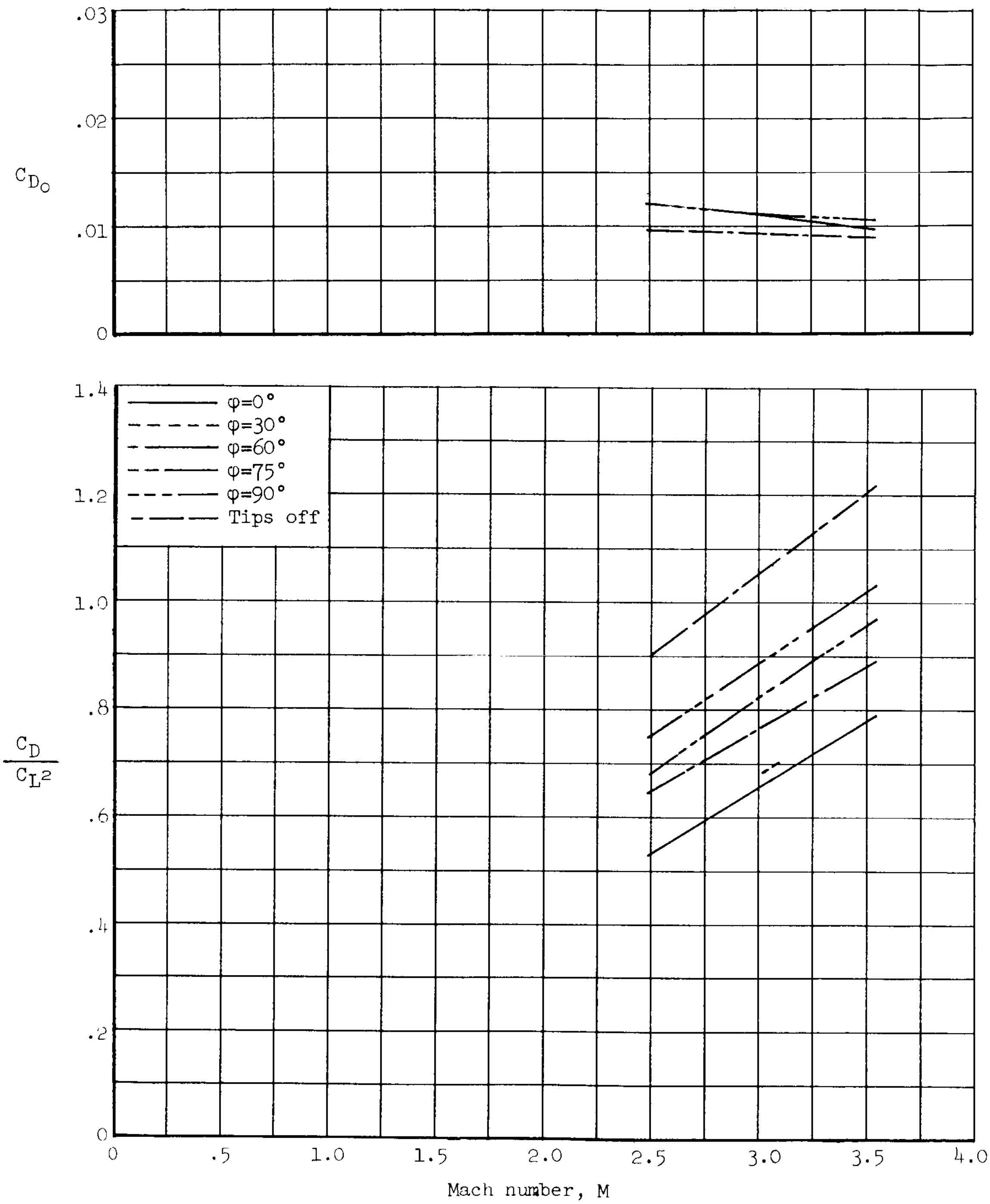

(b) Swept tips

Figure 16.- Concluded.

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[redacted]

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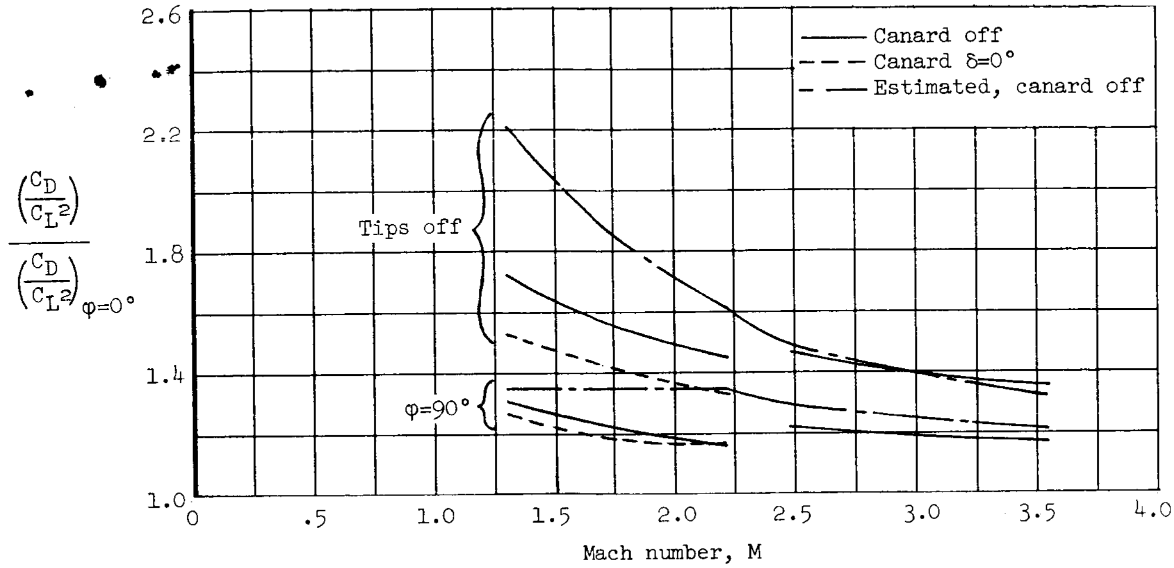
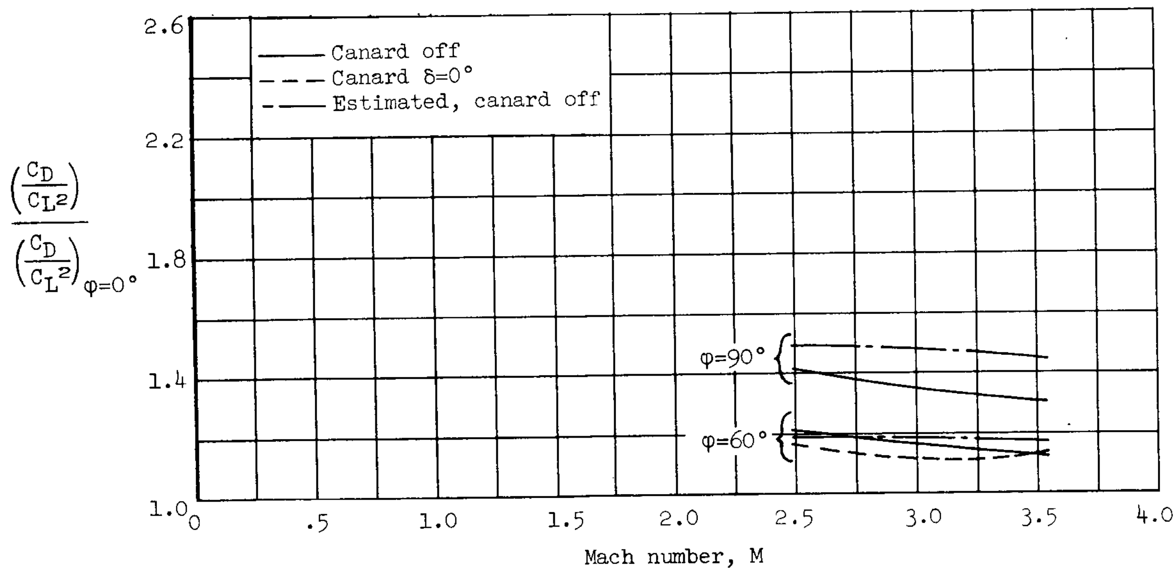


(a) Triangular tips



(b) Swept tips

Figure 17.- Variations with Mach number of the effects on the drag-due-to-lift resulting from deflecting or removing the tips with the canard off and on.

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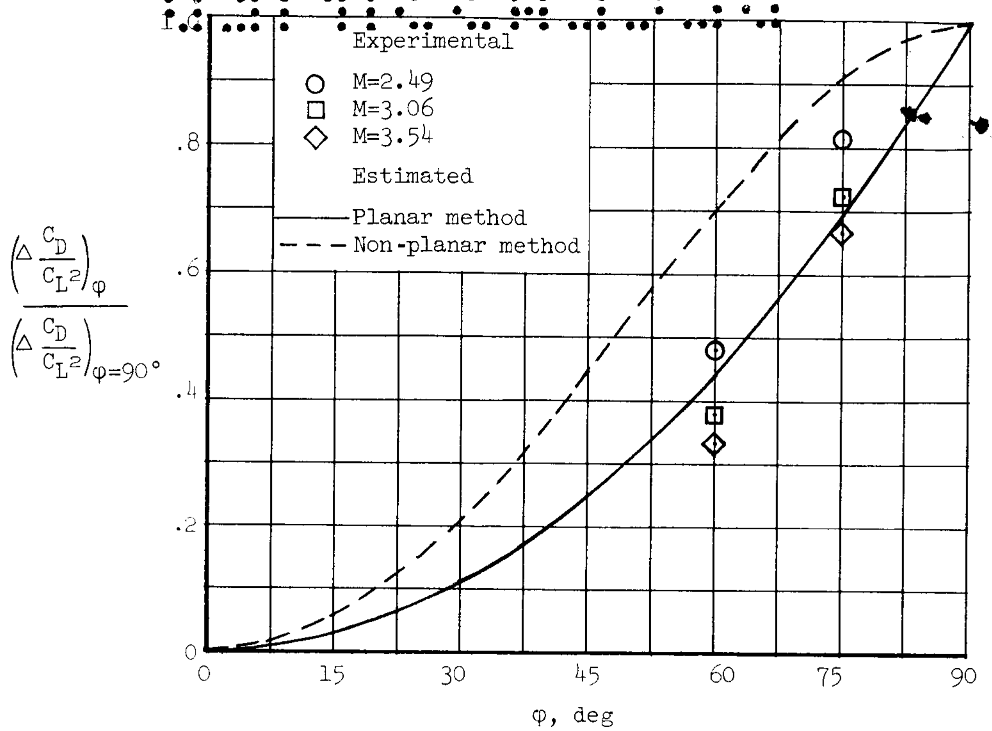
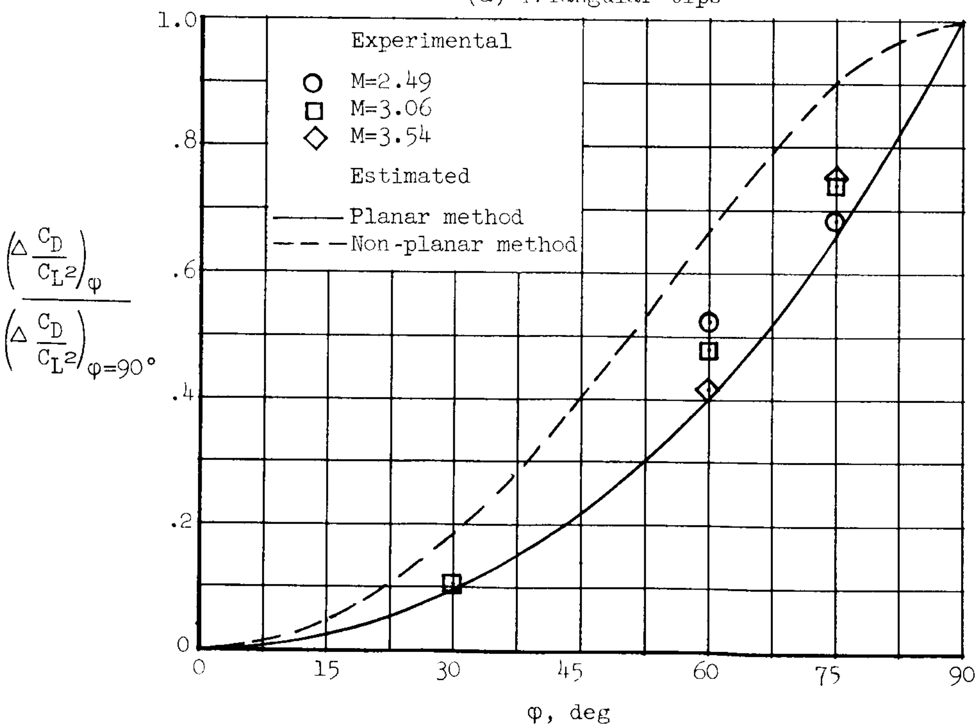
[redacted]



(a) Triangular tips



(b) Swept tips

Figure 18.- Variation of drag-due-to-lift ratio with tip deflection with the canard off.

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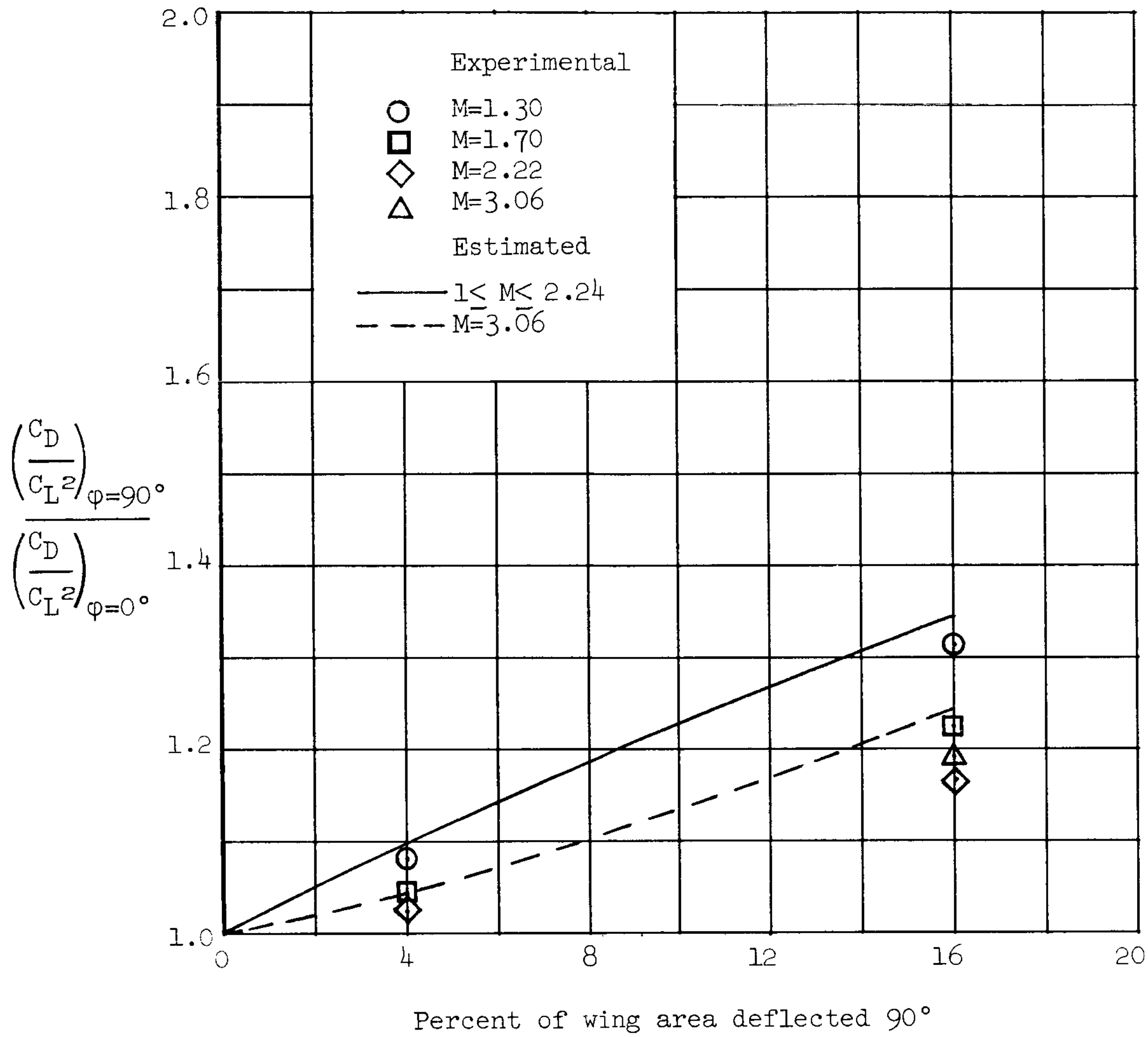

Figure 19.- Effect of amount of area deflected 90° on the drag-due-to-lift ratio for triangular tips configurations with no canard.

[redacted]

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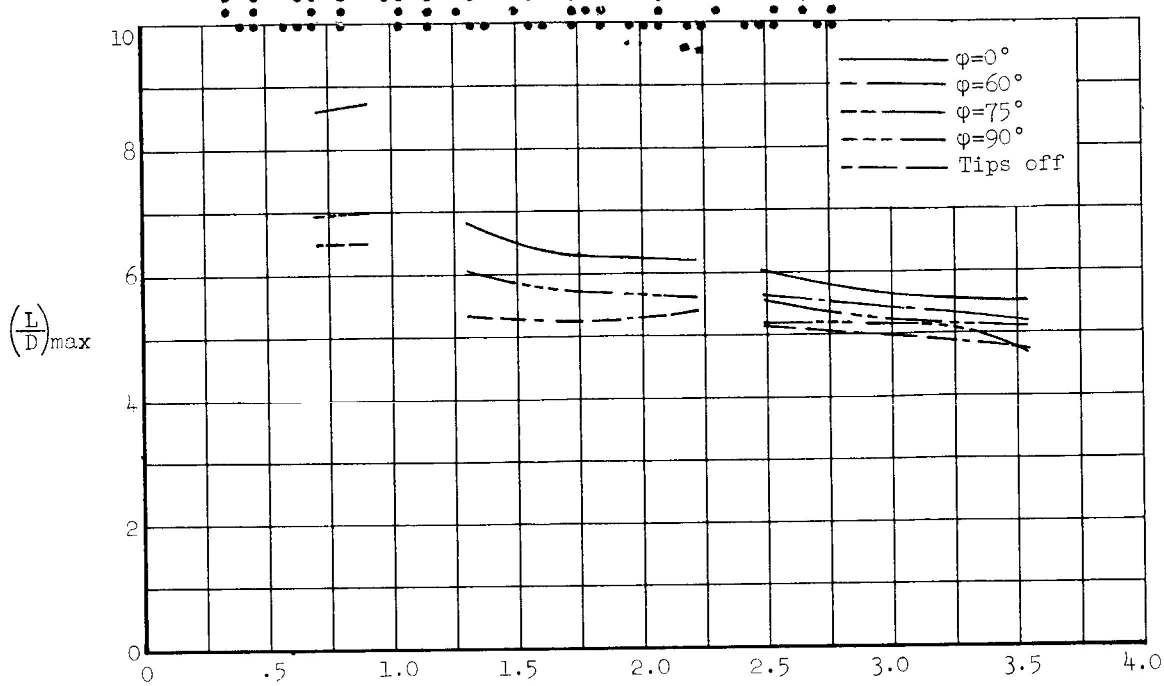
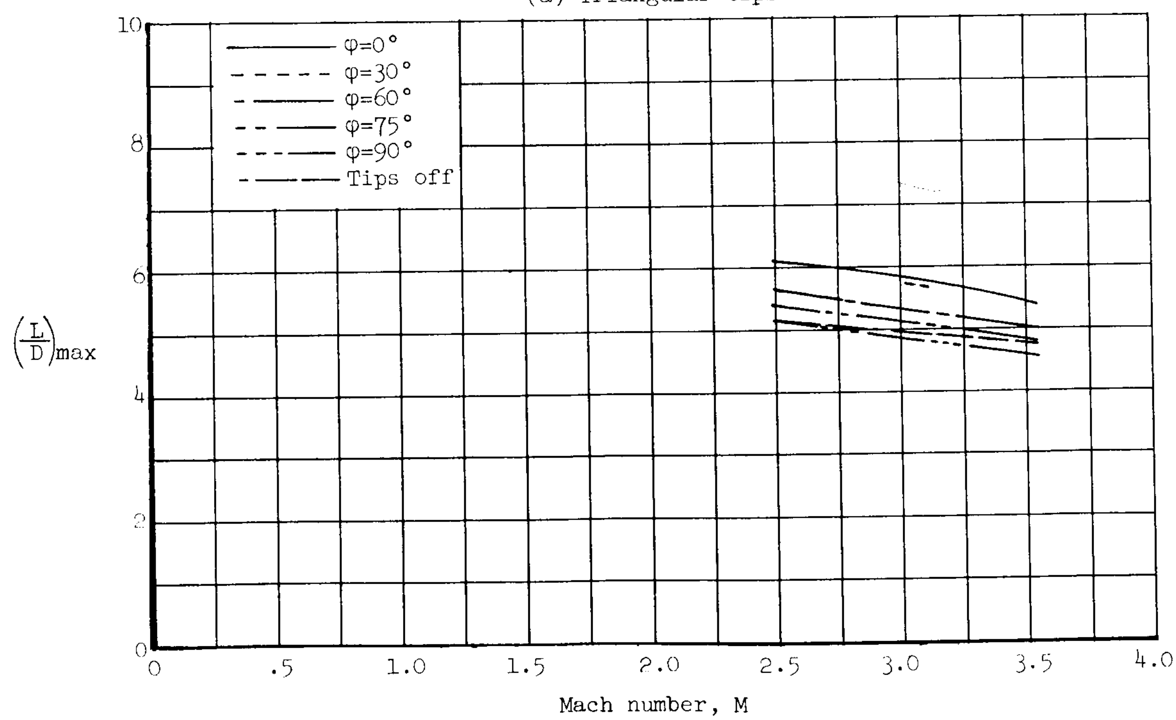


(a) Triangular tips



(b) Swept tips

Figure 20.- Variation with Mach number of the effects of tip deflection or tip removal on the maximum lift-drag ratio with the canard off.

[redacted]

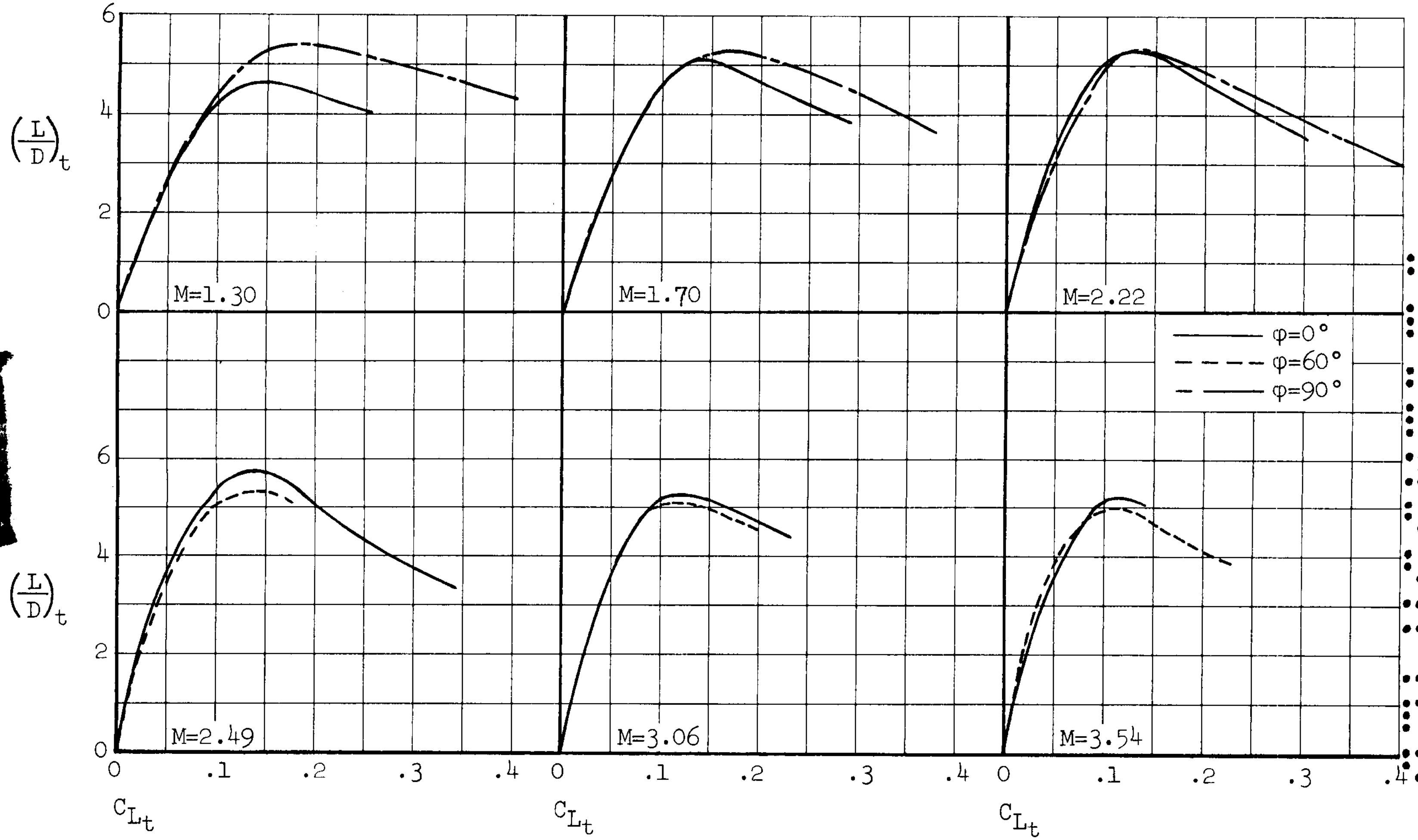


Figure 21.- Effects of deflecting the triangular tips on the trimmed lift-drag ratios.

DECLASSIFIED [redacted]

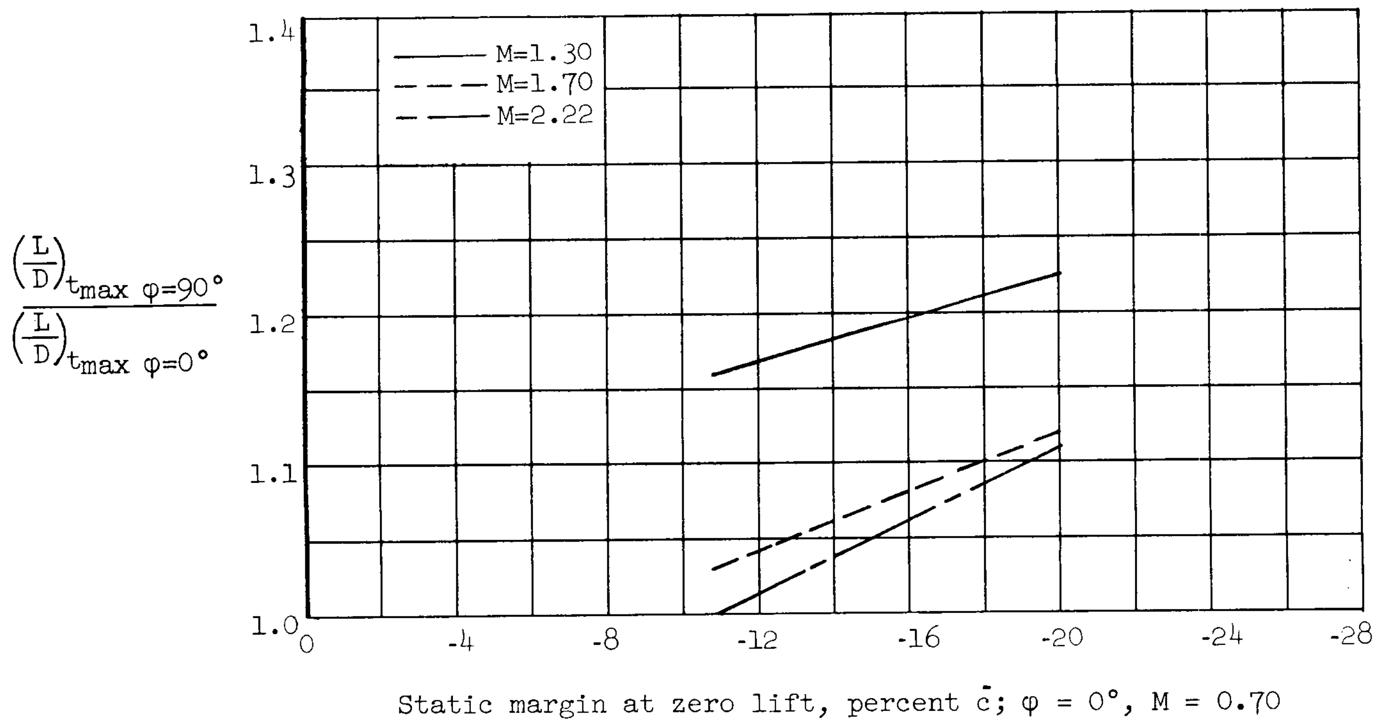
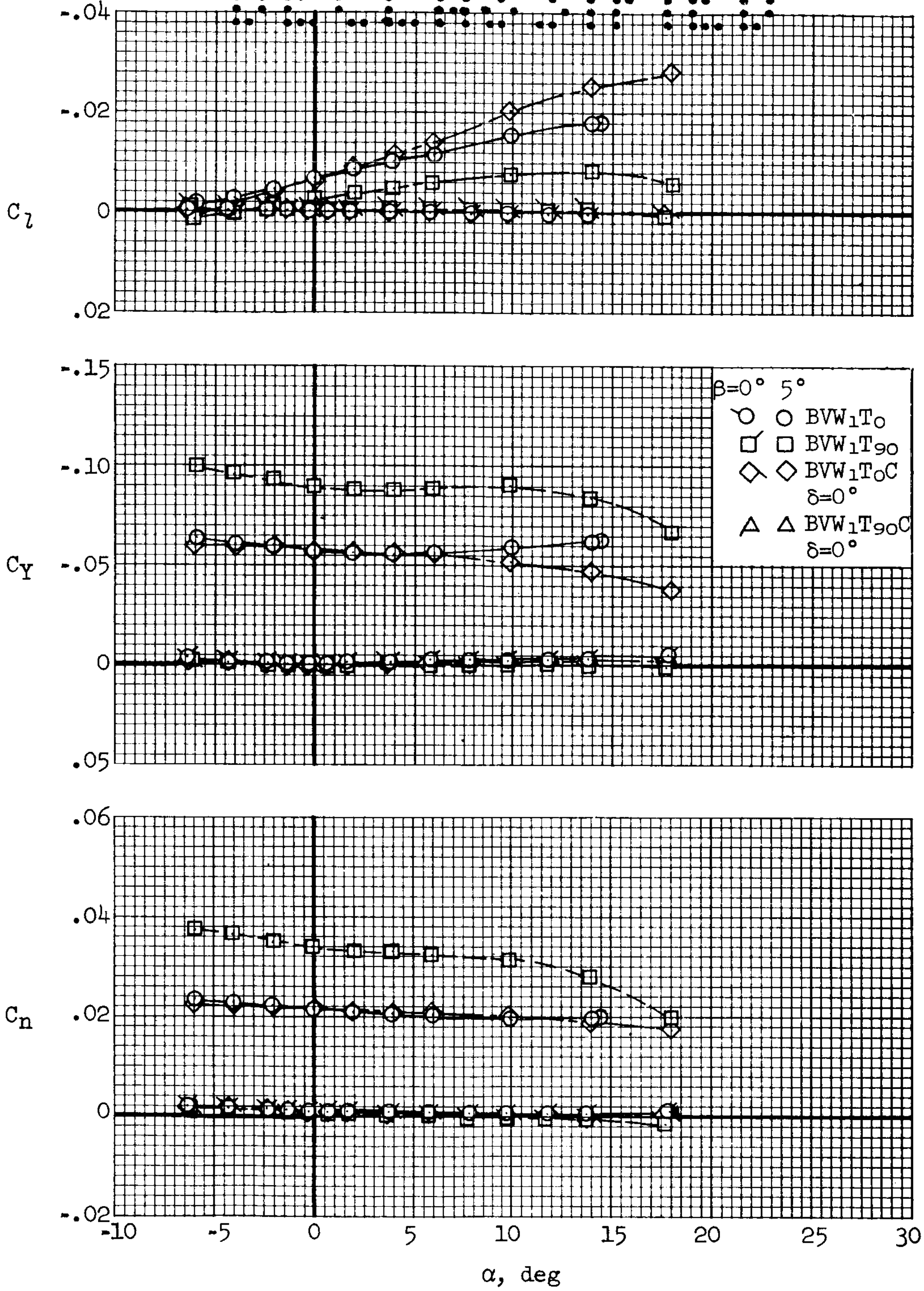


Figure 22.- Variation with static margin of the effects of triangular tip deflection on the maximum lift-drag ratio.

[redacted]

[redacted]

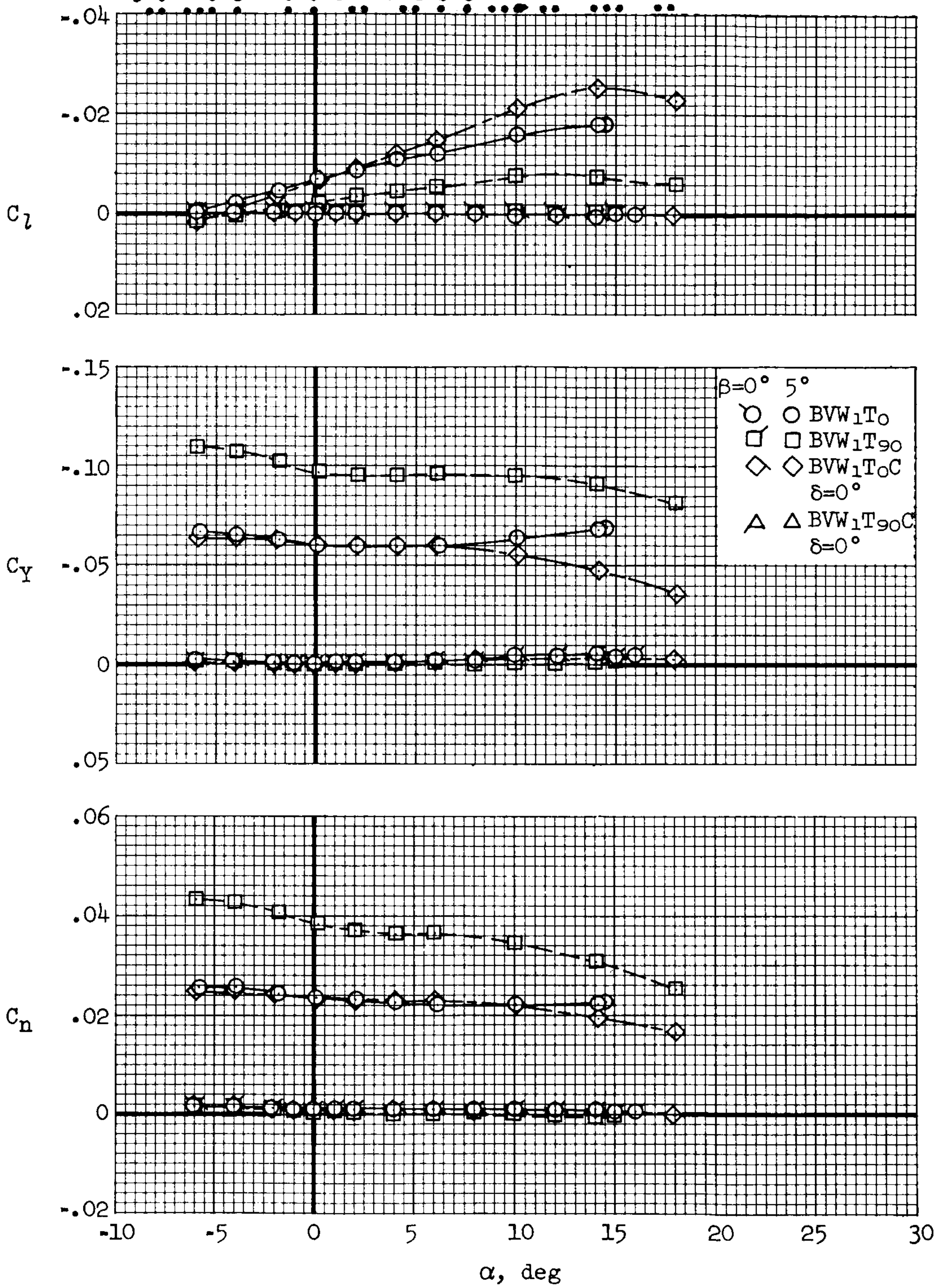


(a) M = 0.70

Figure 23.- Effect of tip deflection on the lateral and directional characteristics of the triangular wing configuration at 0° and 5° sideslip with the canard off and on.

[redacted]

[redacted]



(b) M = 0.90

Figure 23.- Continued.

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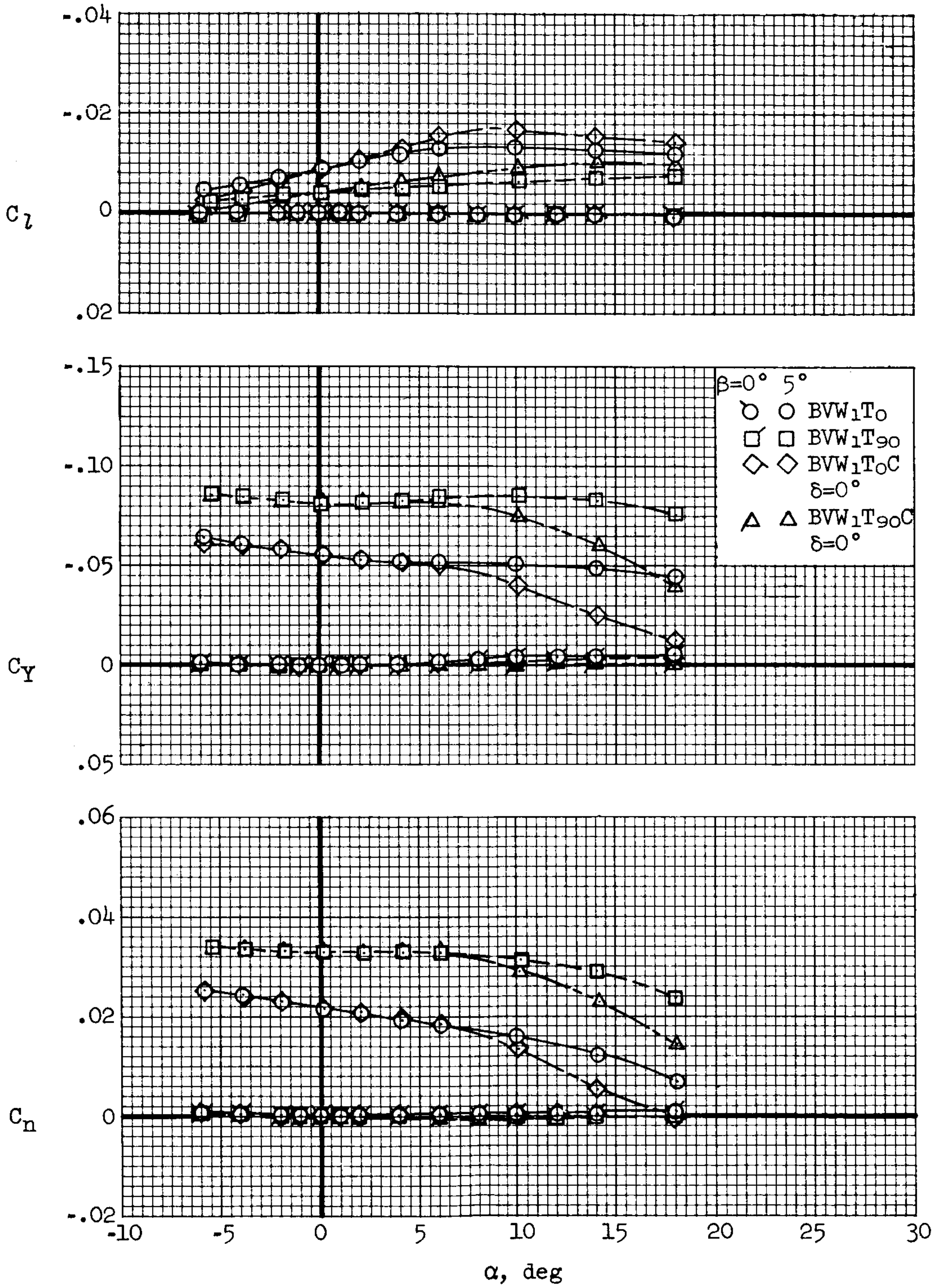
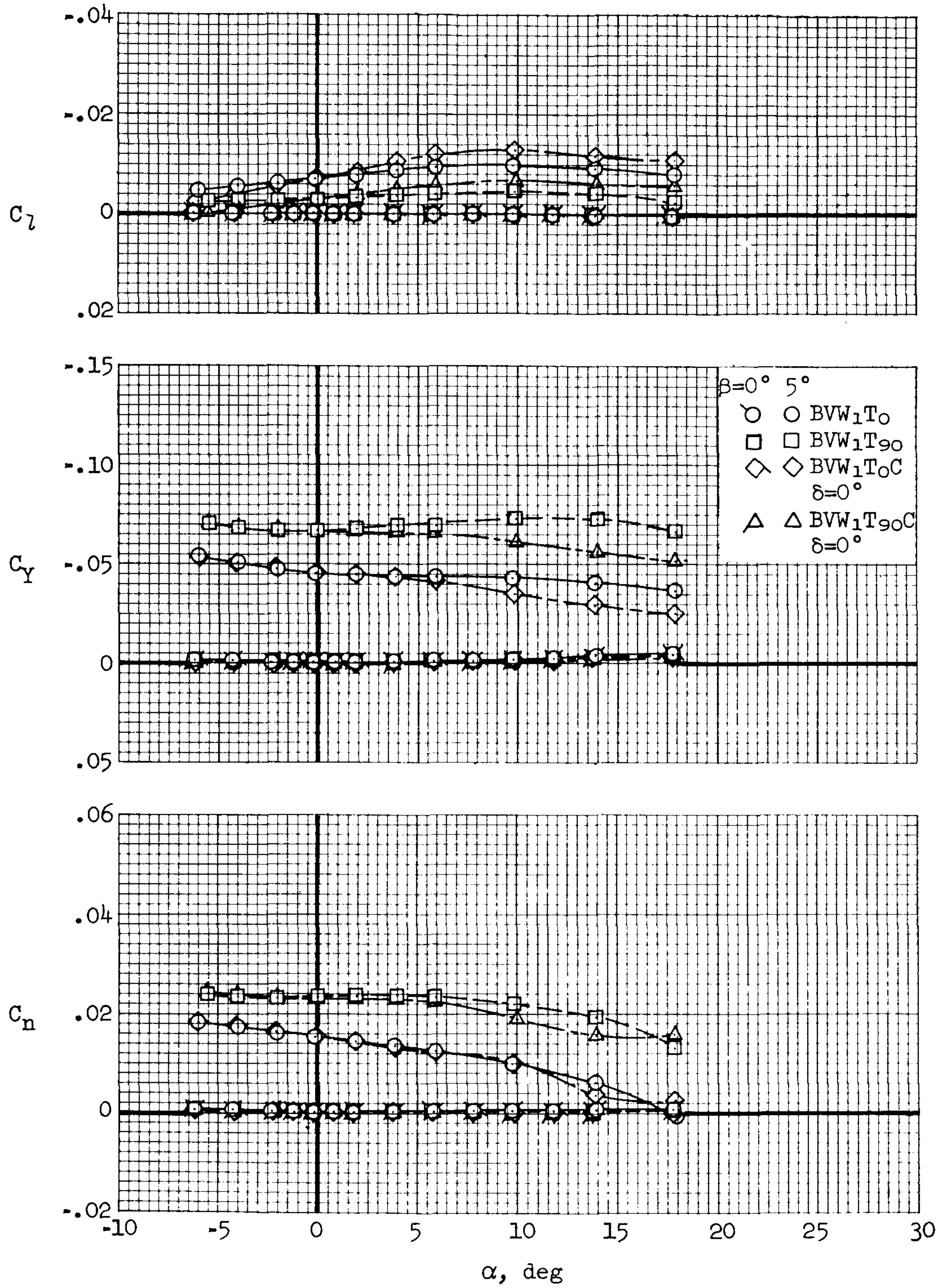


(c) M = 1.30

Figure 23.- Continued.

[redacted]



(d) M = 1.70

Figure 23.- Continued.

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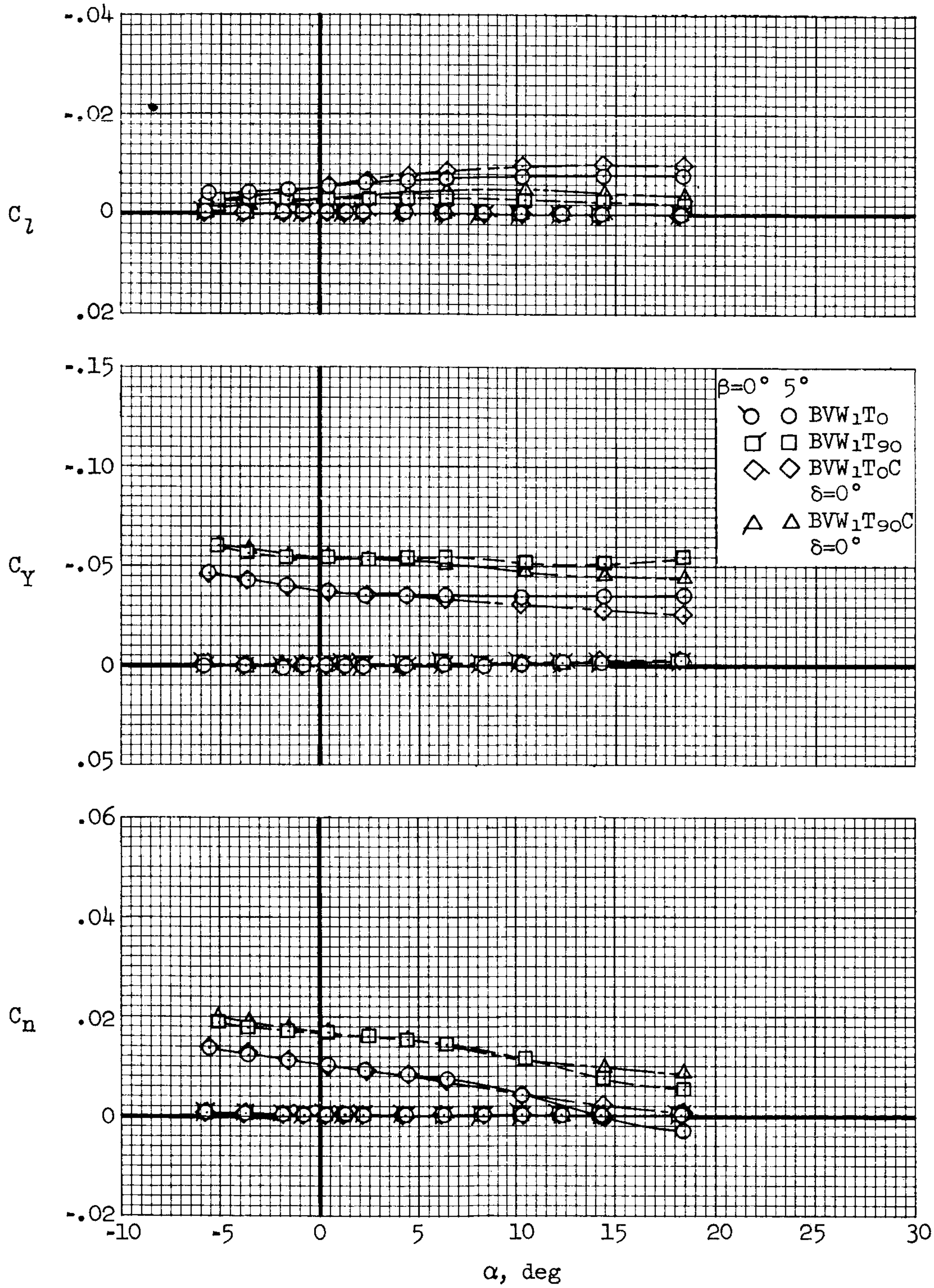

(e) M = 2.22

Figure 23.- Concluded.

[redacted]

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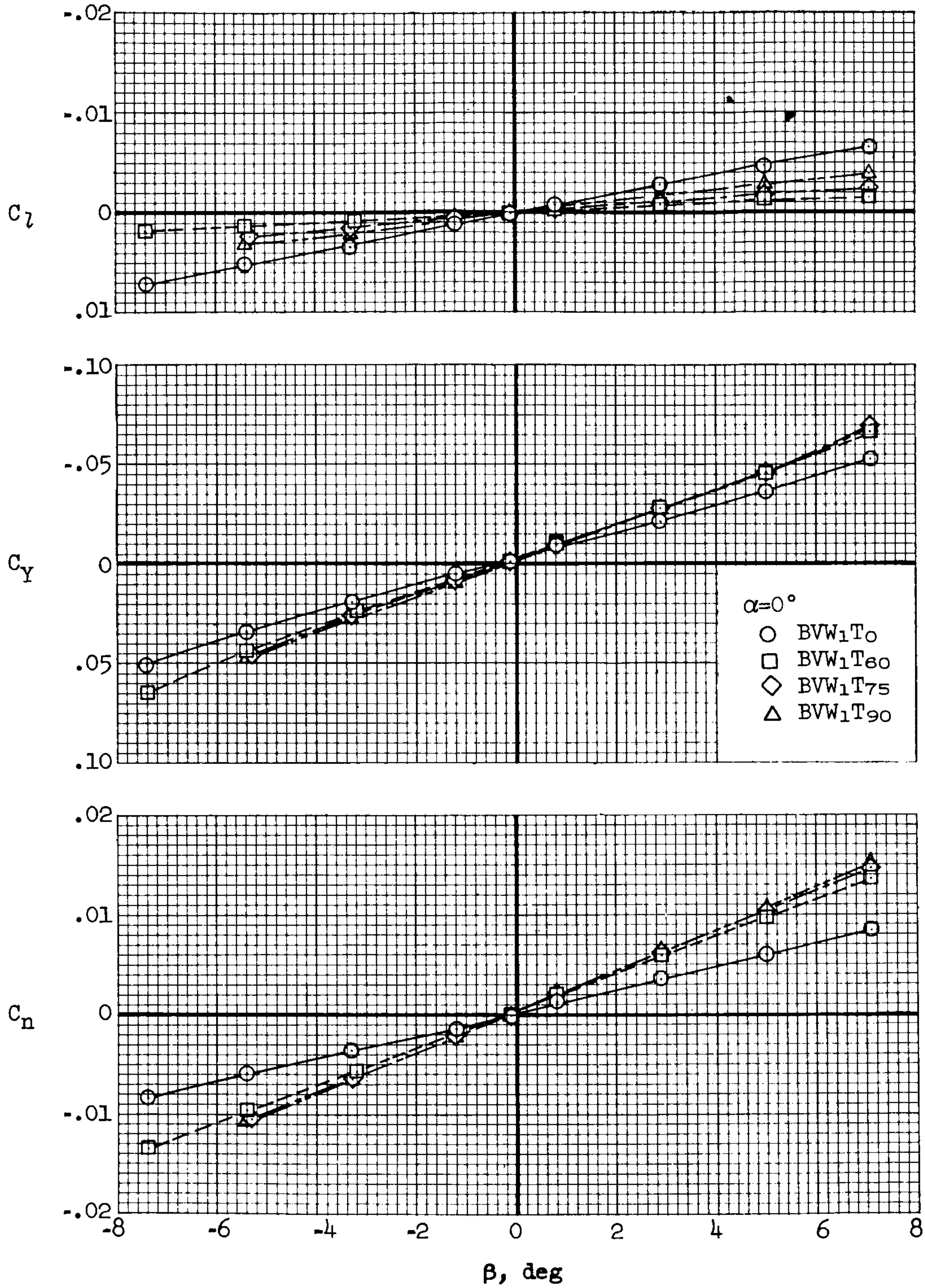

M = 3.06

Figure 24.- Effect of tip deflection on the lateral and directional characteristics of the triangular wing configuration at 0° angle of attack.

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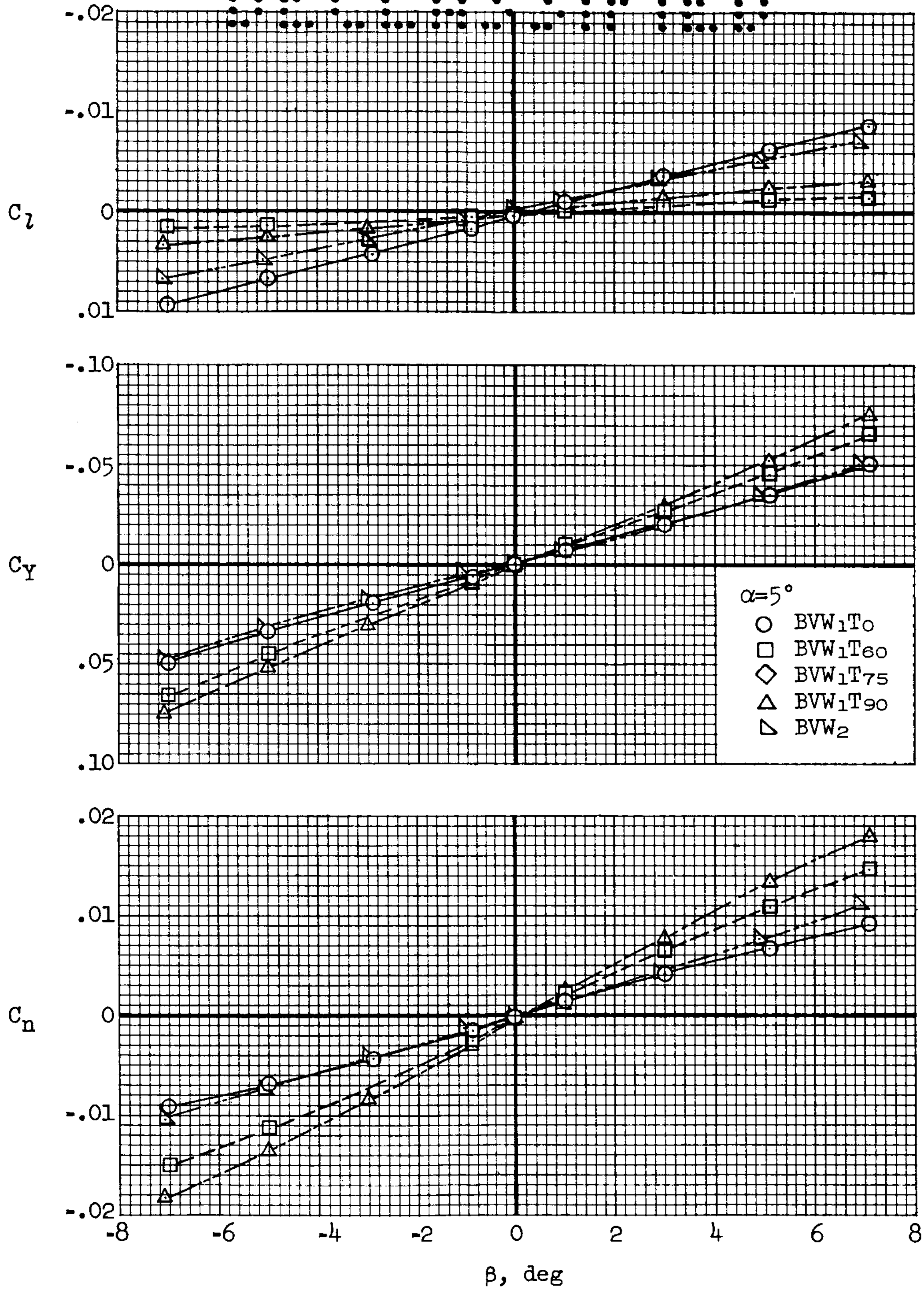

(a) M = 2.49

Figure 25.- Effects of tip deflection and tip removal on the lateral and directional characteristics of the triangular wing configuration at 5° angle of attack.

[redacted]

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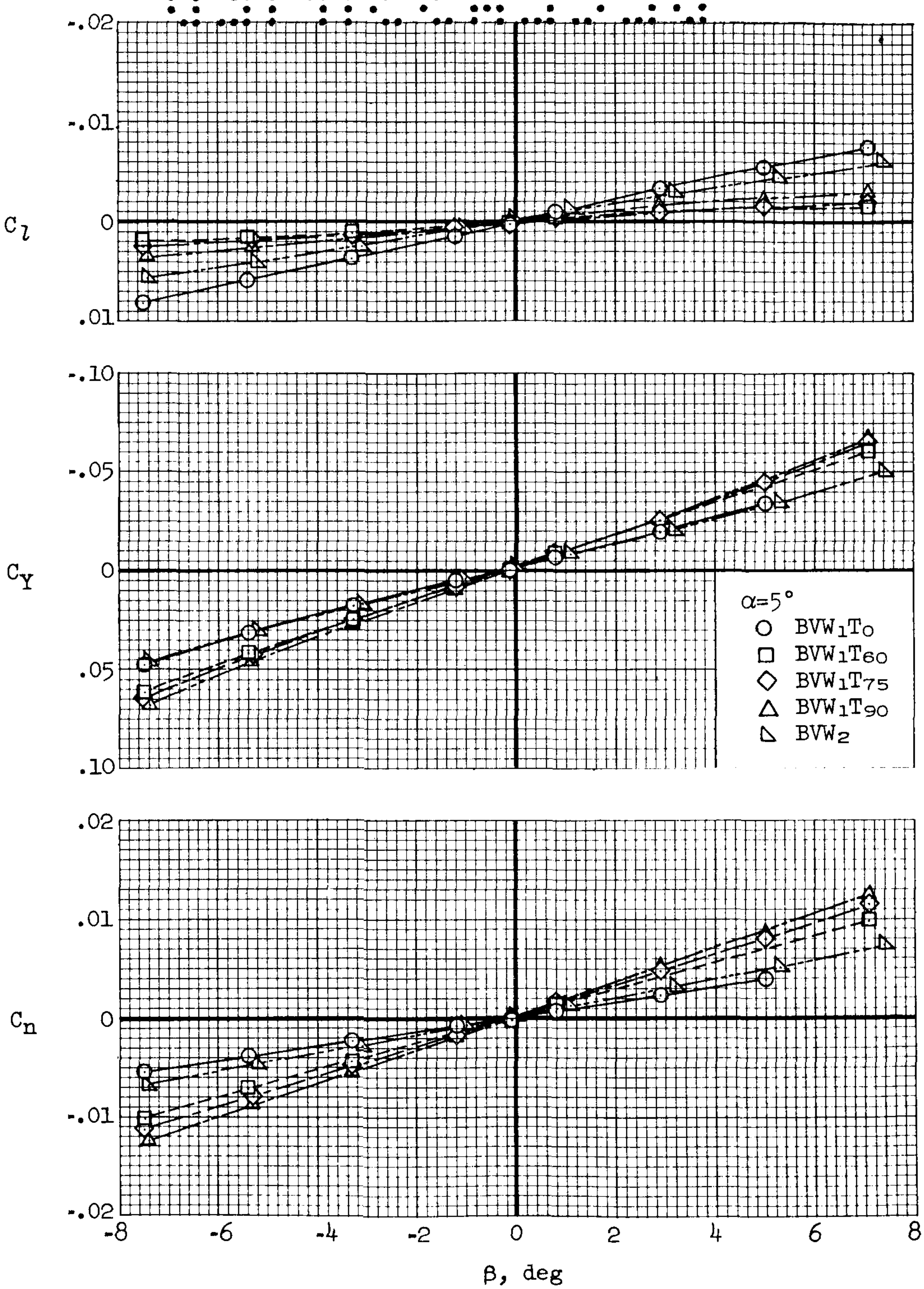

(b) M = 3.06

Figure 25.- Continued.

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1

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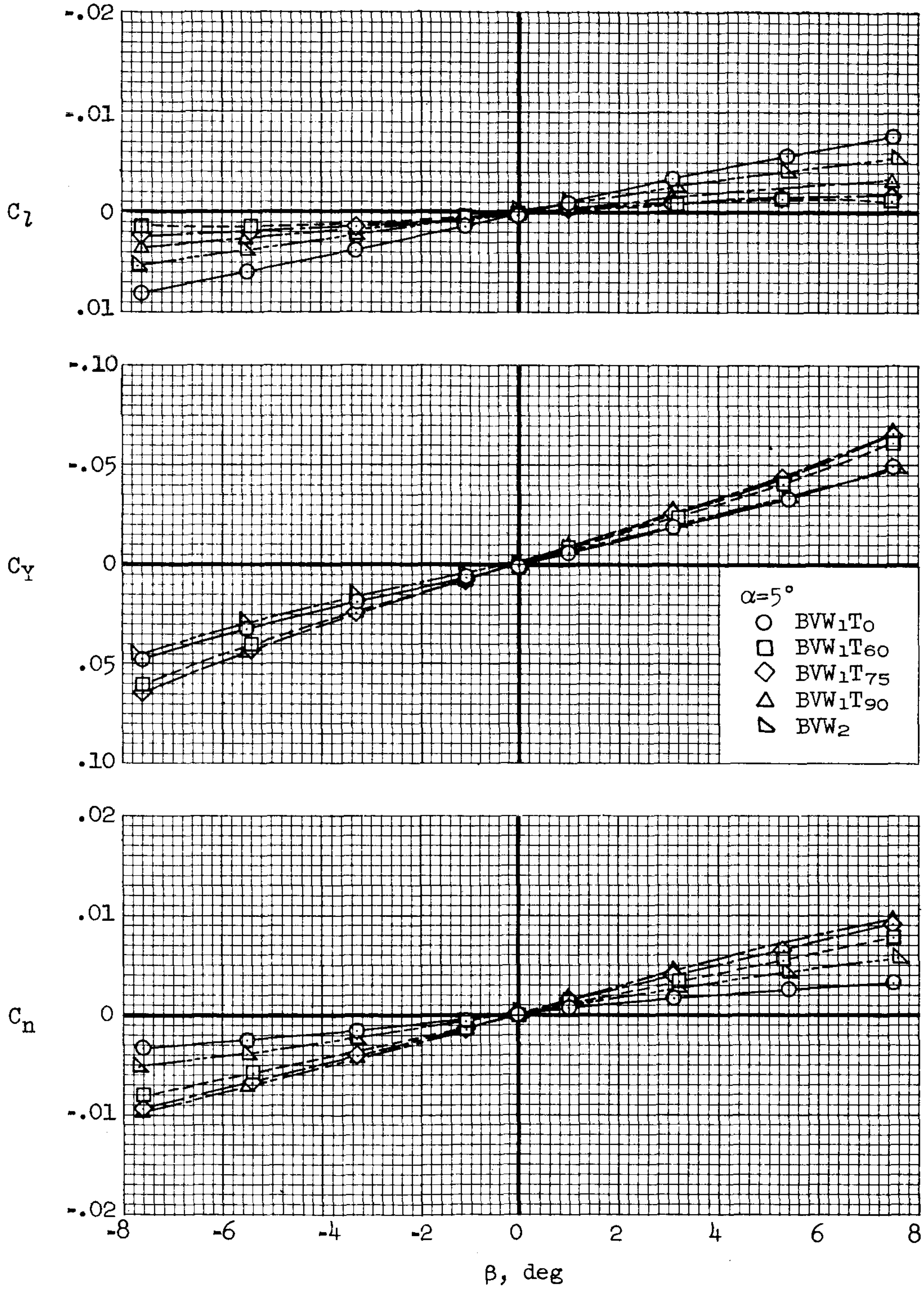
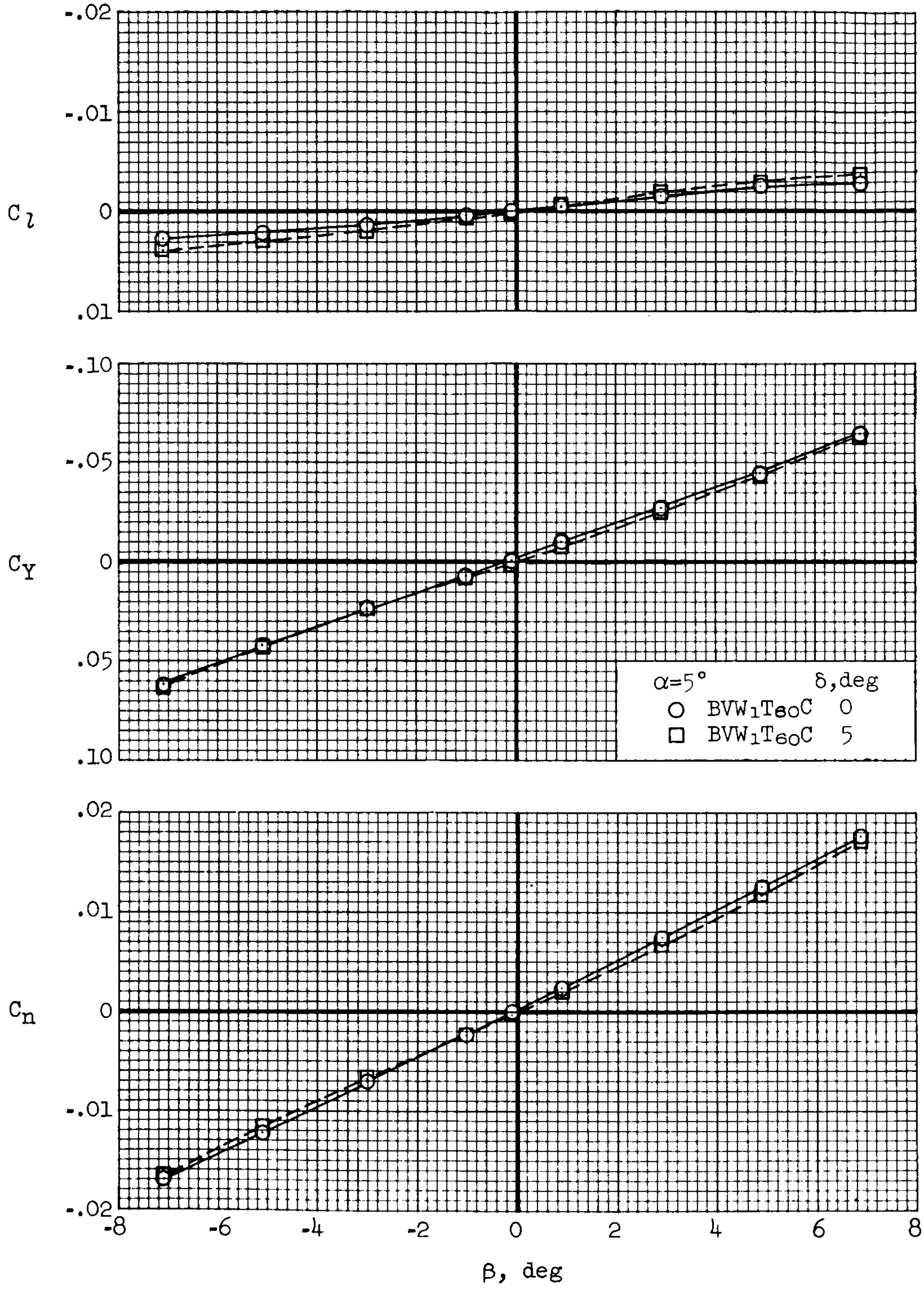


(c) M = 3.54

Figure 25.- Concluded.

[redacted]



(a) M = 2.49

Figure 26.- Effect of canard deflection on the lateral and directional characteristics of the triangular wing configuration at 5° angle of attack with tip deflected 60°.

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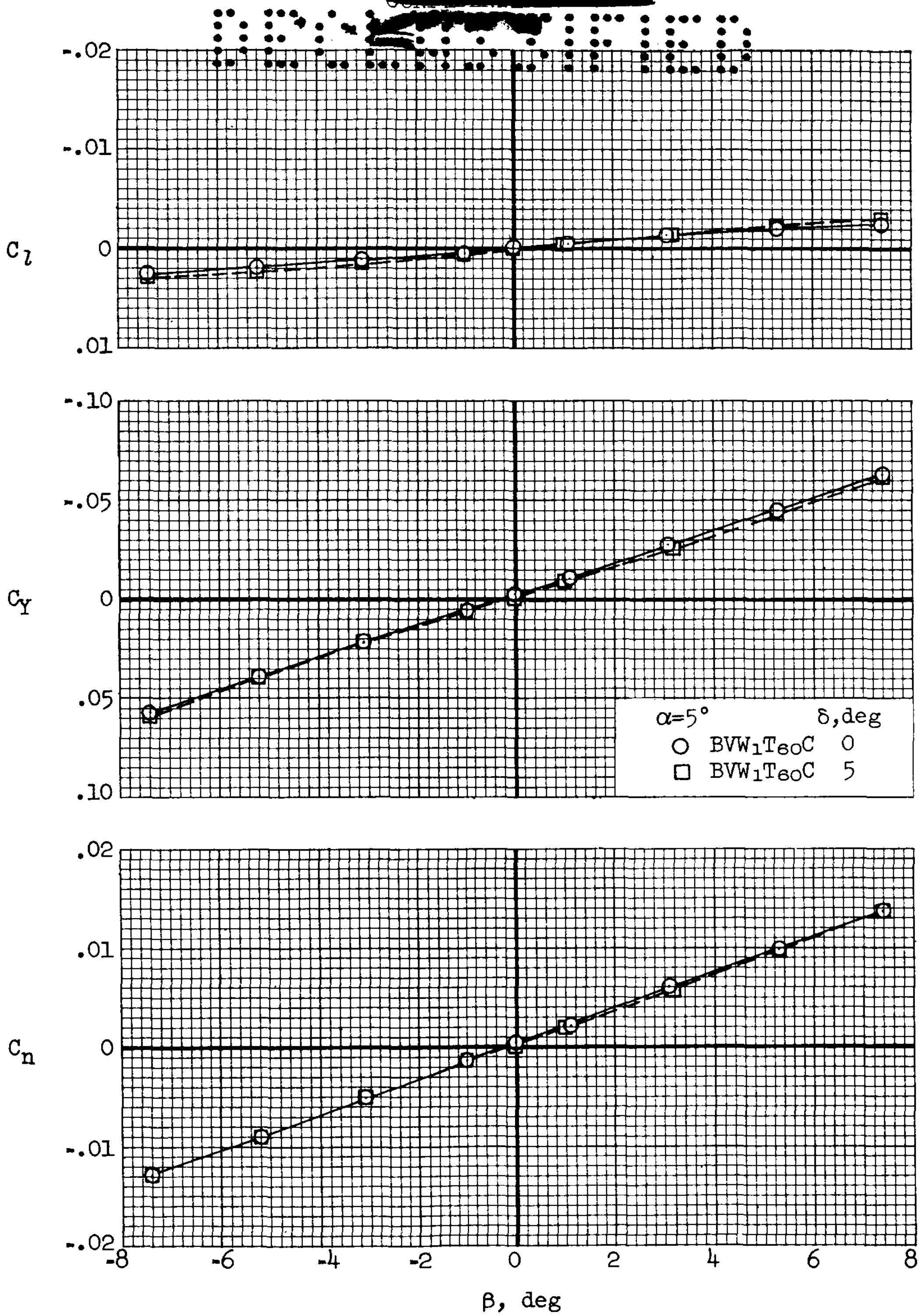

(b) M = 3.06

Figure 26.- Continued.

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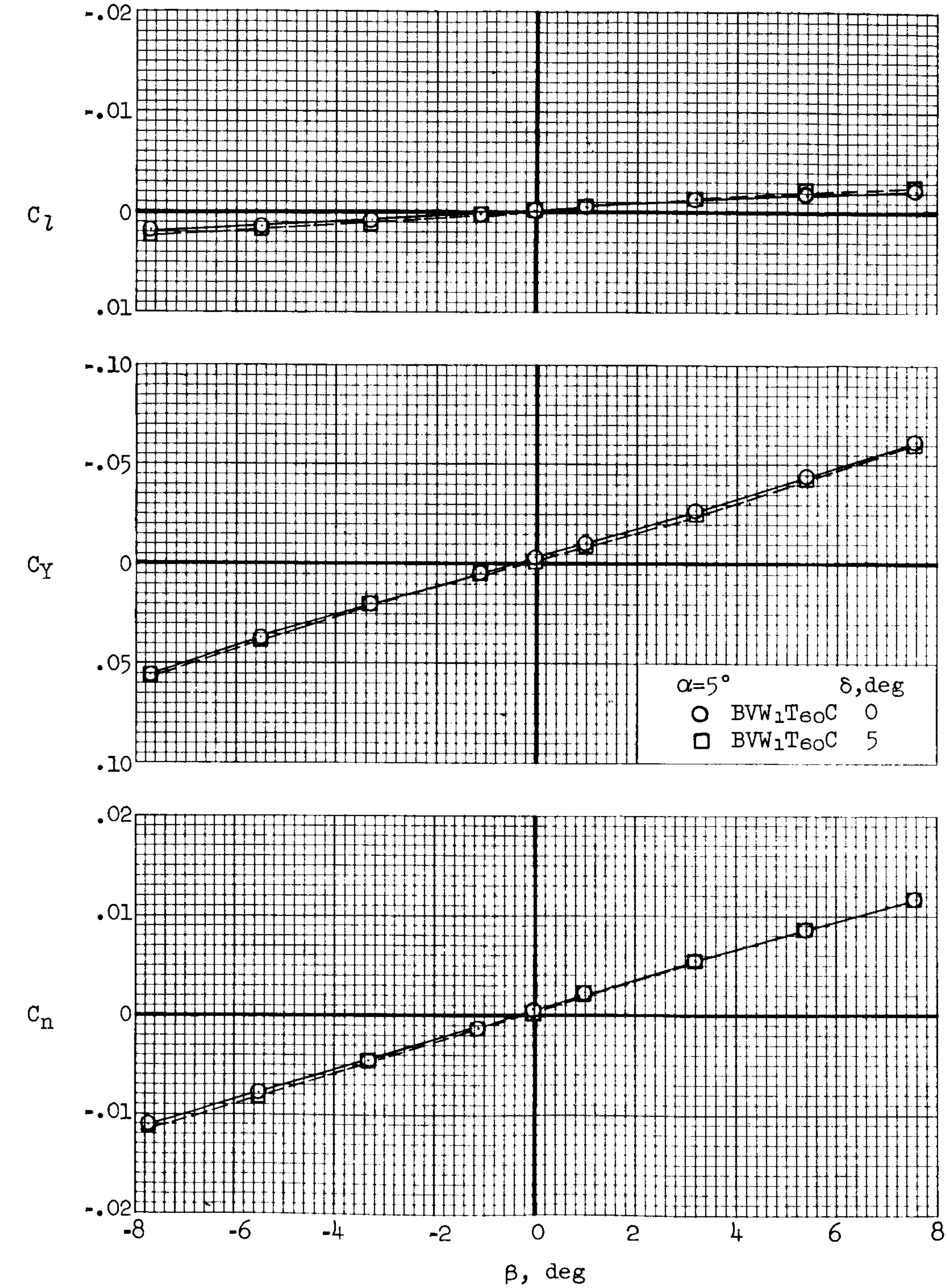

(c) M = 3.54

Figure 26.- Concluded.

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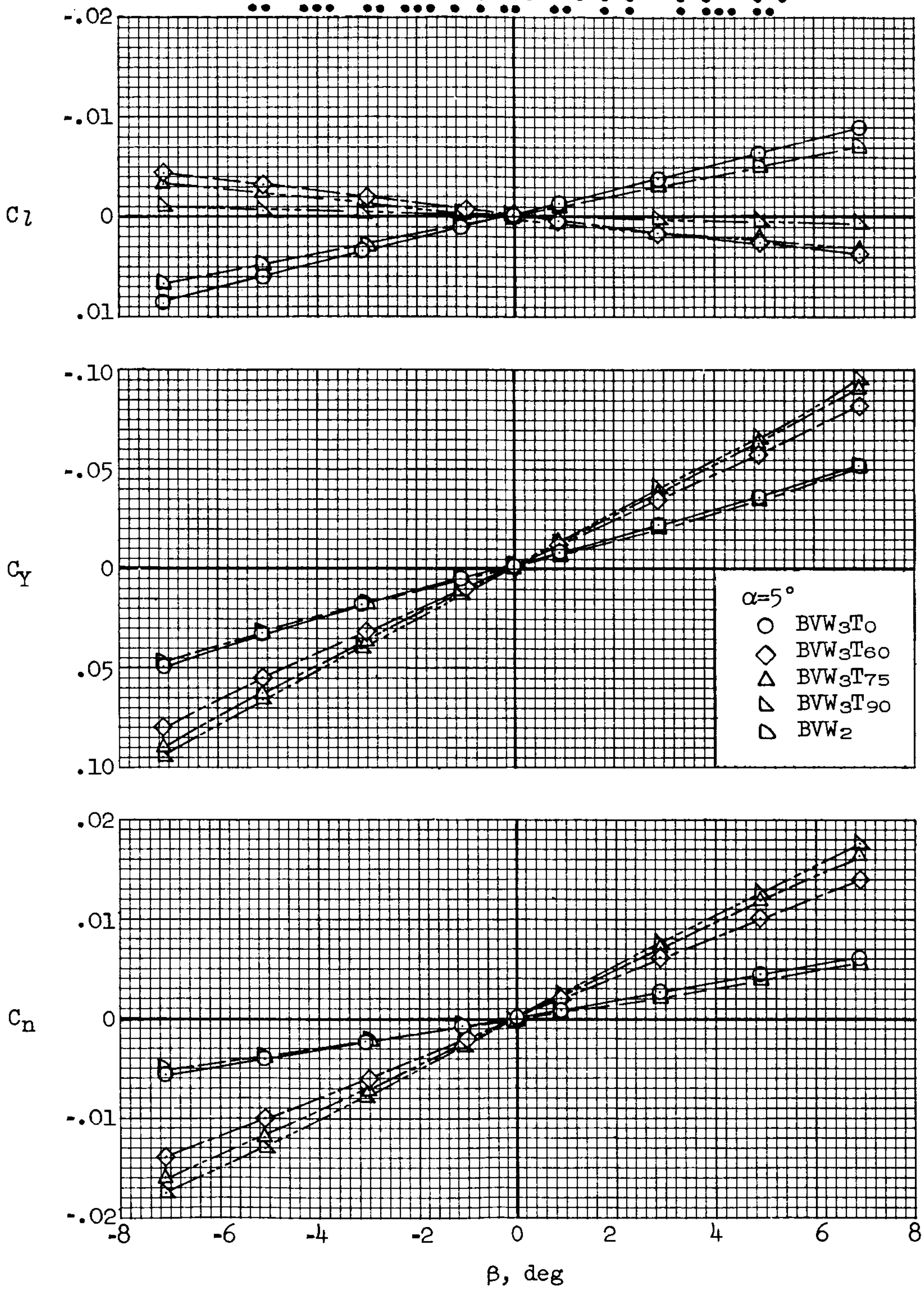

(a) M = 2.49

Figure 27.- Effect of tip deflection on the lateral and directional characteristics of the swept wing configuration at 5° angle of attack.

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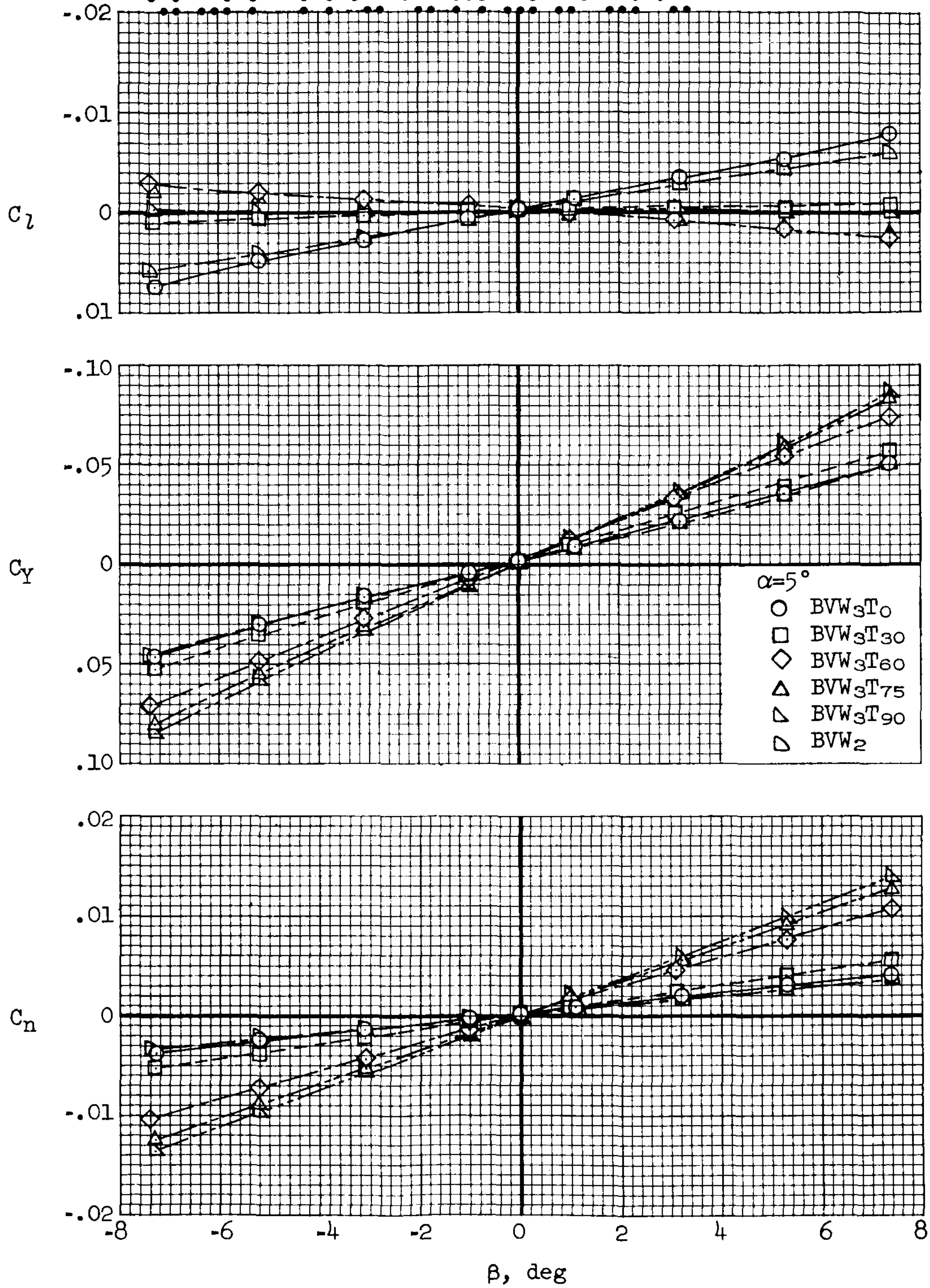

(b) M = 3.06

Figure 27.- Continued.

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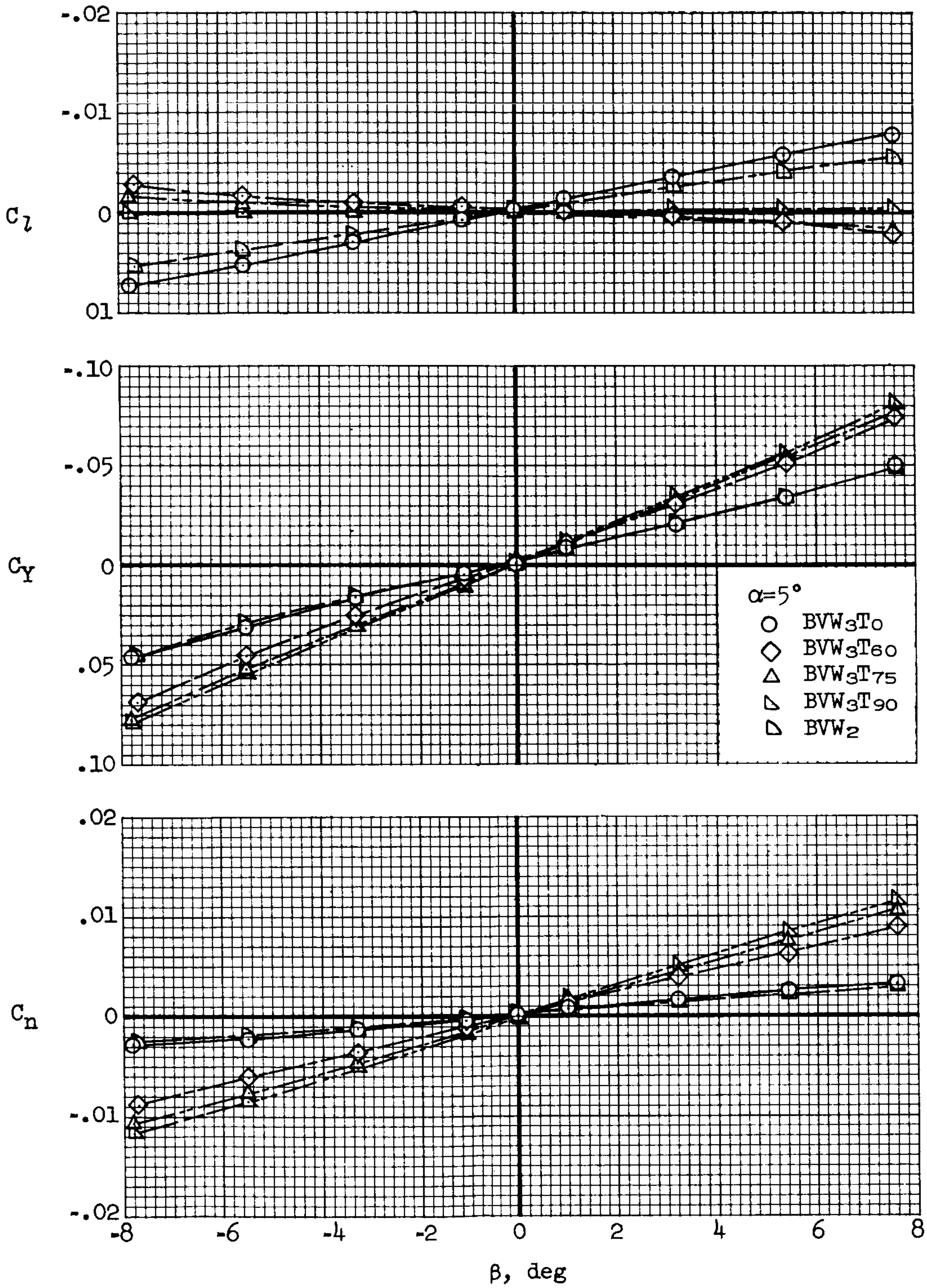

(c) M = 3.54

Figure 27.- Concluded.

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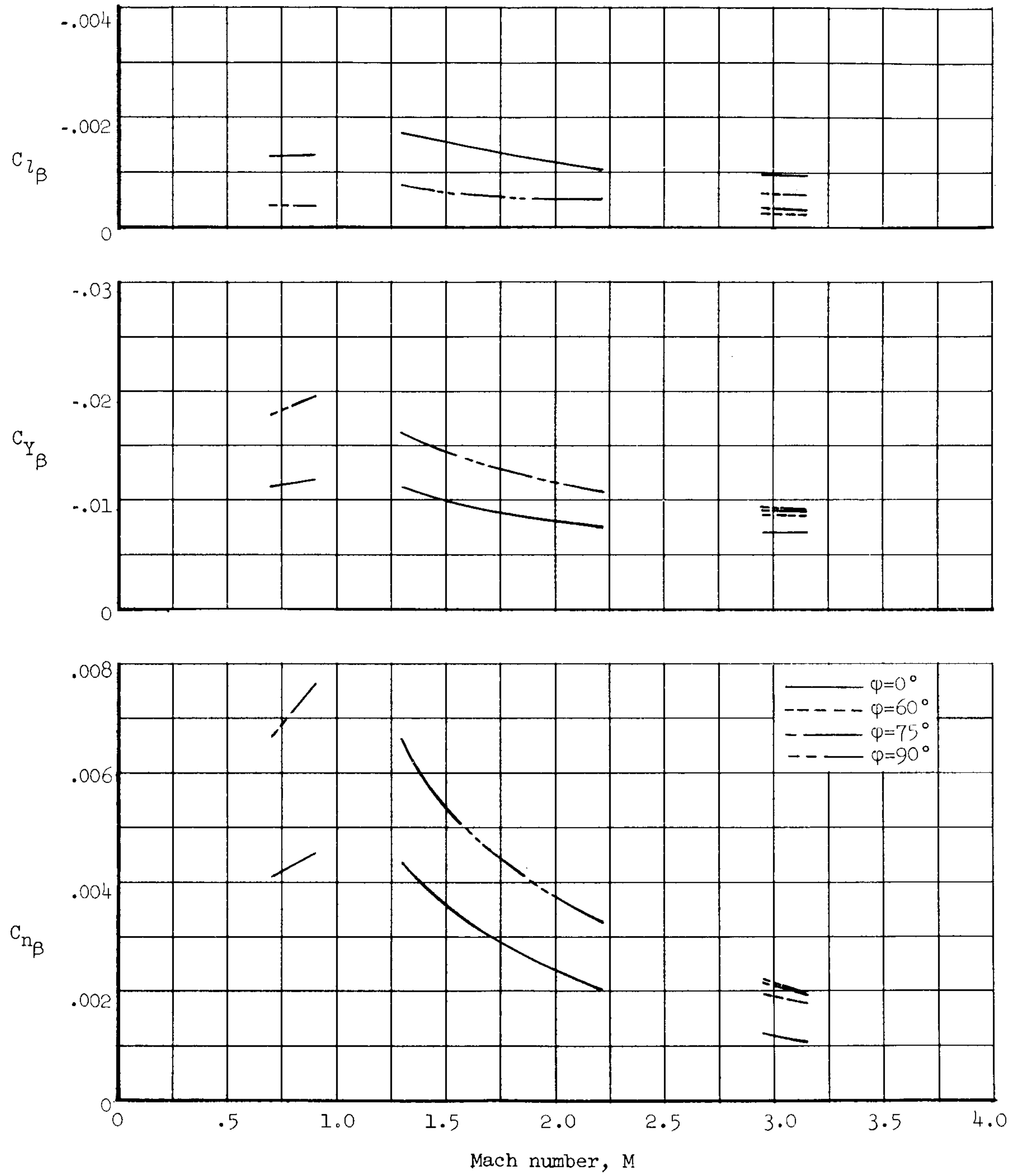

(a) $\alpha = 0°$

Figure 28.- Variation with Mach number of the lateral and directional incremental derivatives at constant angles of attack resulting from deflecting the triangular tips with the canard off.

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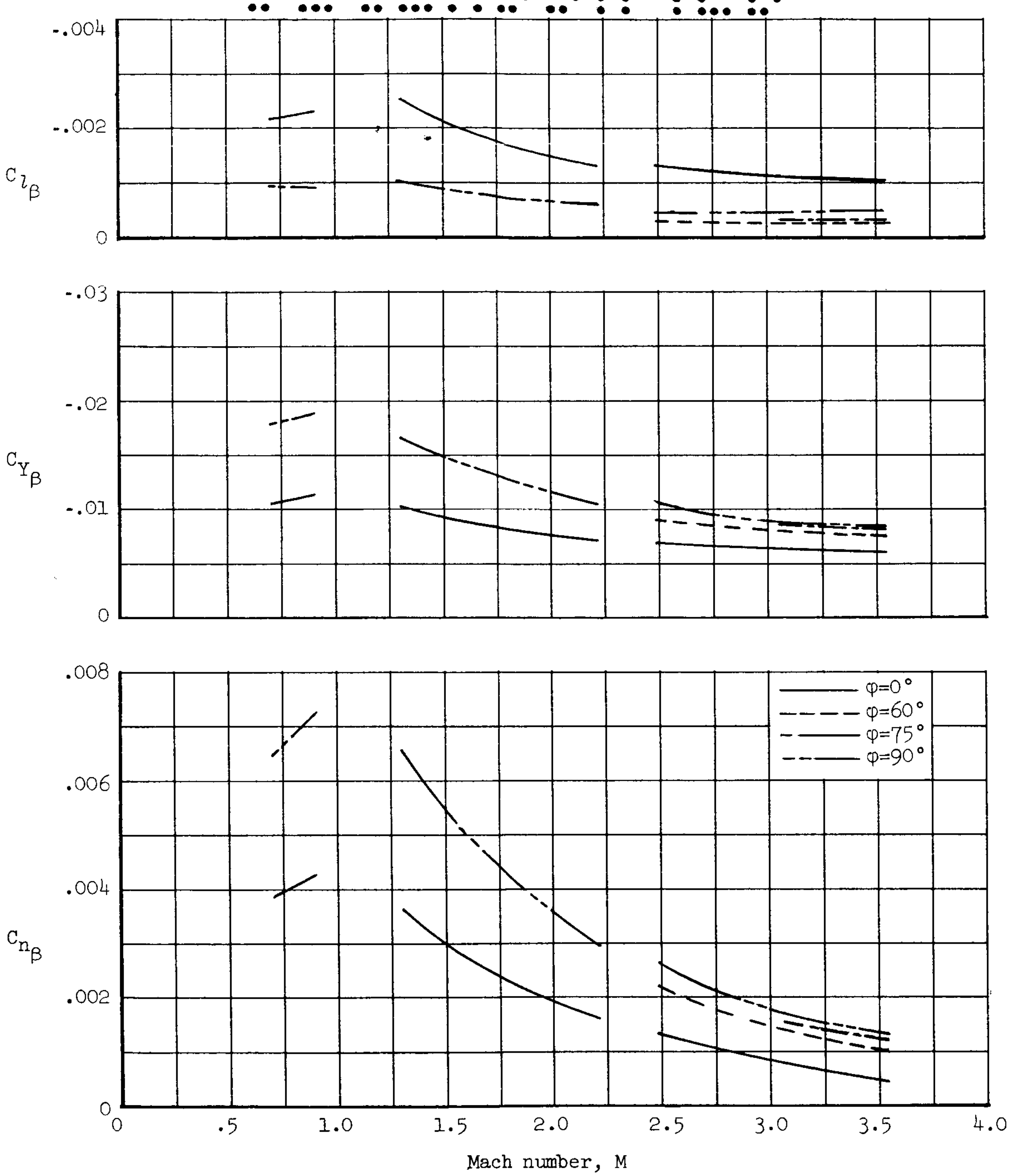
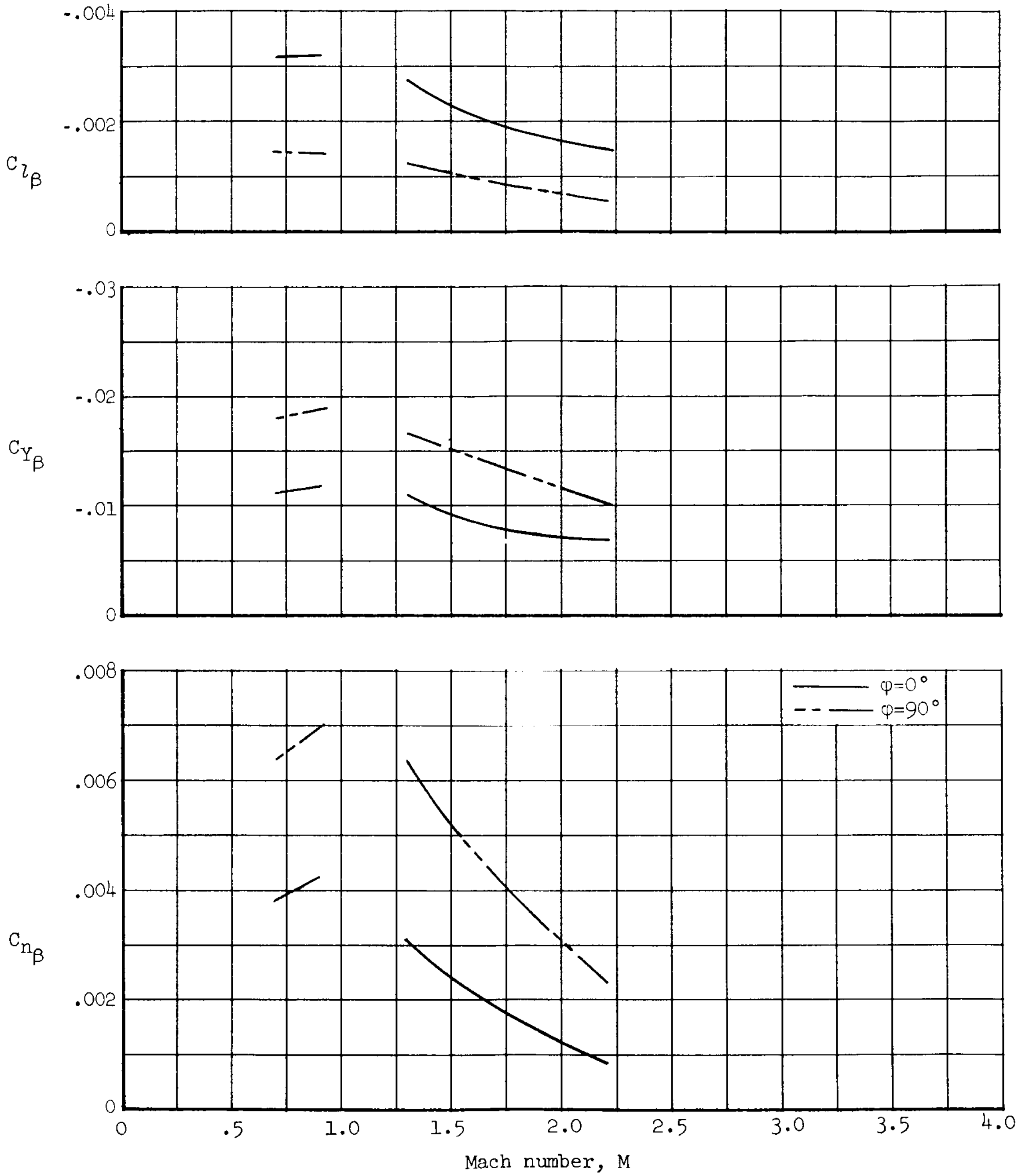


(b) $\alpha = 5°$

Figure 28.- Continued.



(c) $\alpha = 10°$

Figure 28.- Concluded.

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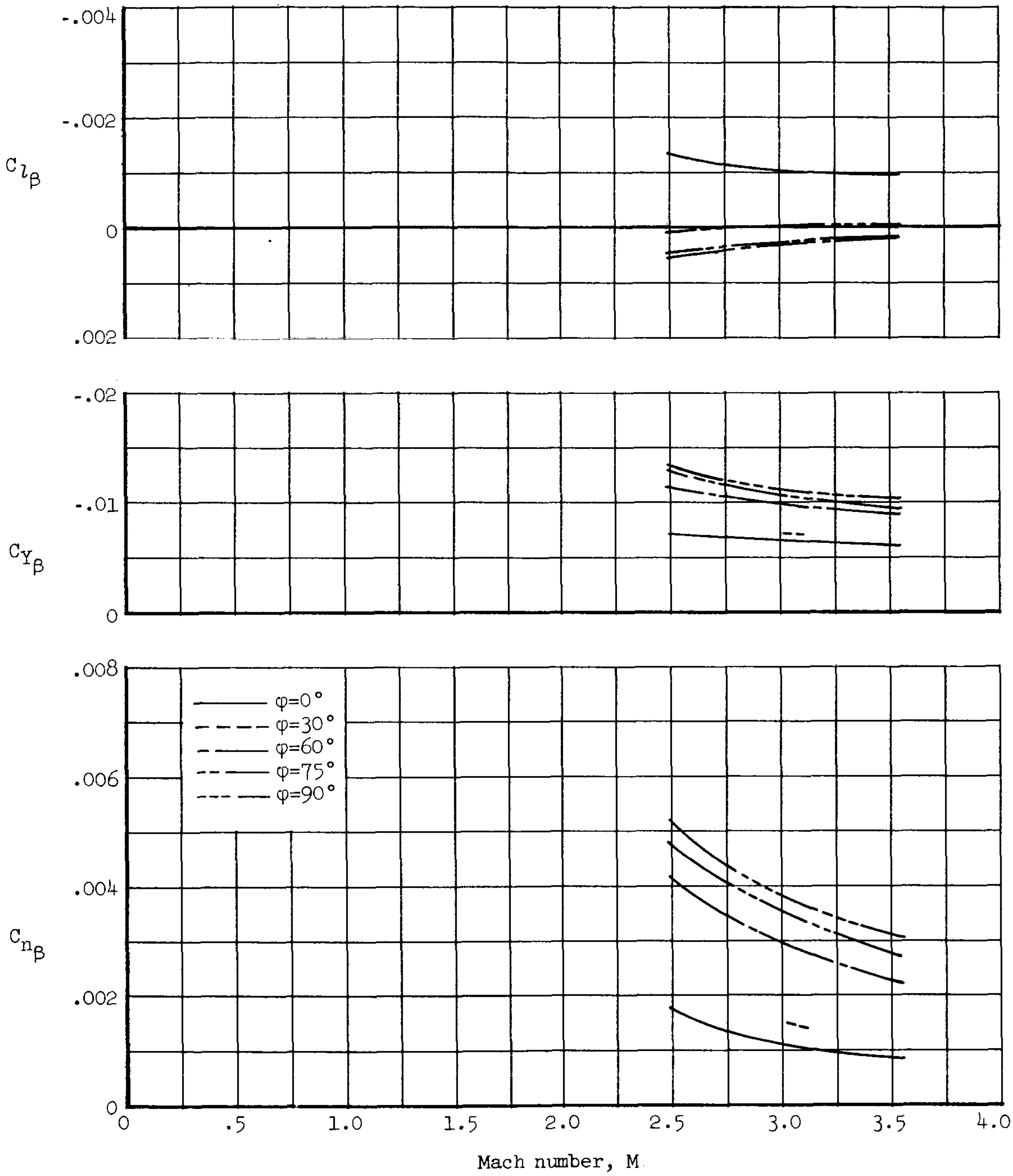

$\alpha = 5°$

Figure 29.- Variation with Mach number of the lateral and directional incremental derivatives of constant angle of attack resulting from deflecting the swept tips with the canard off.

[redacted]

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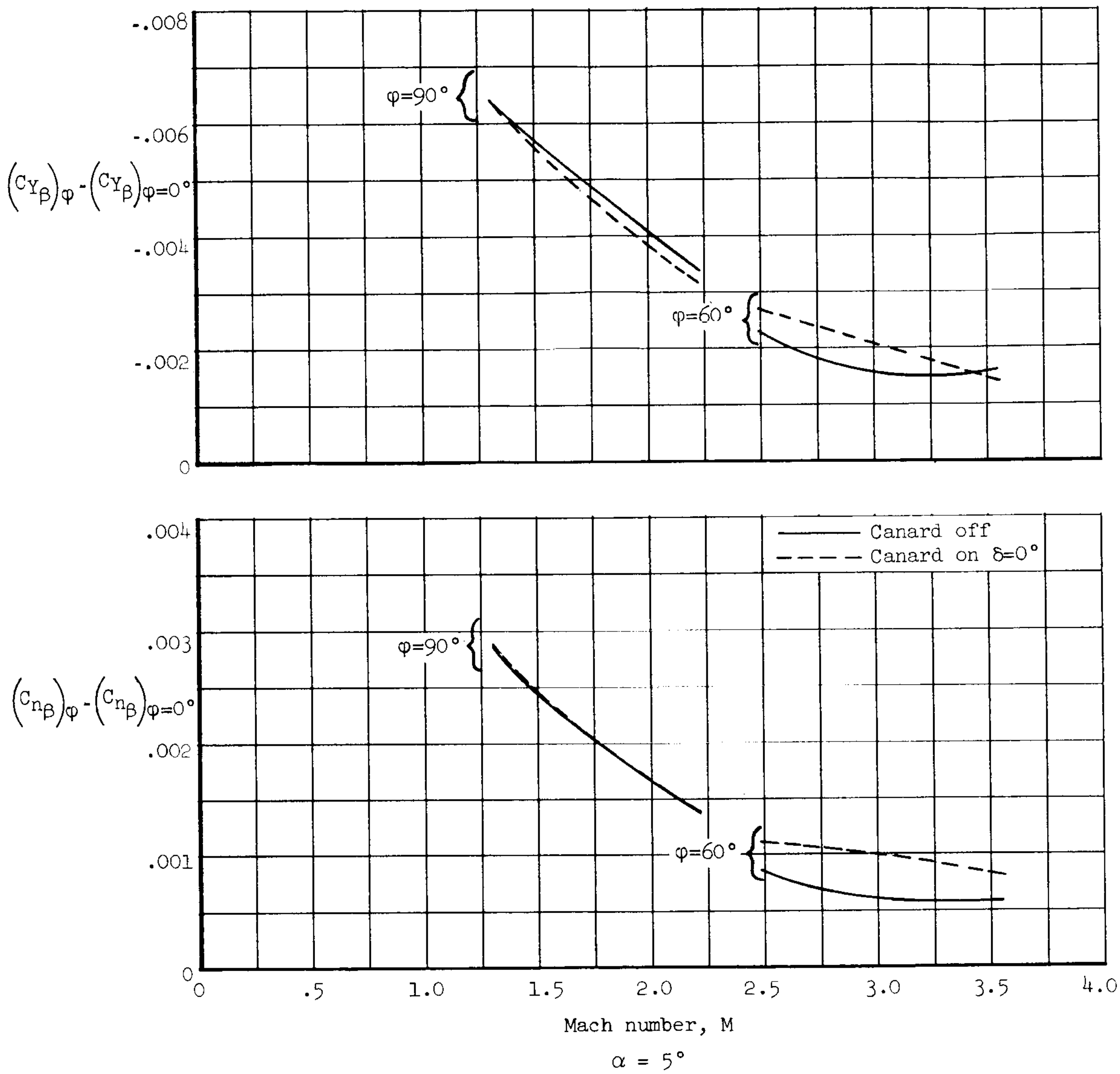
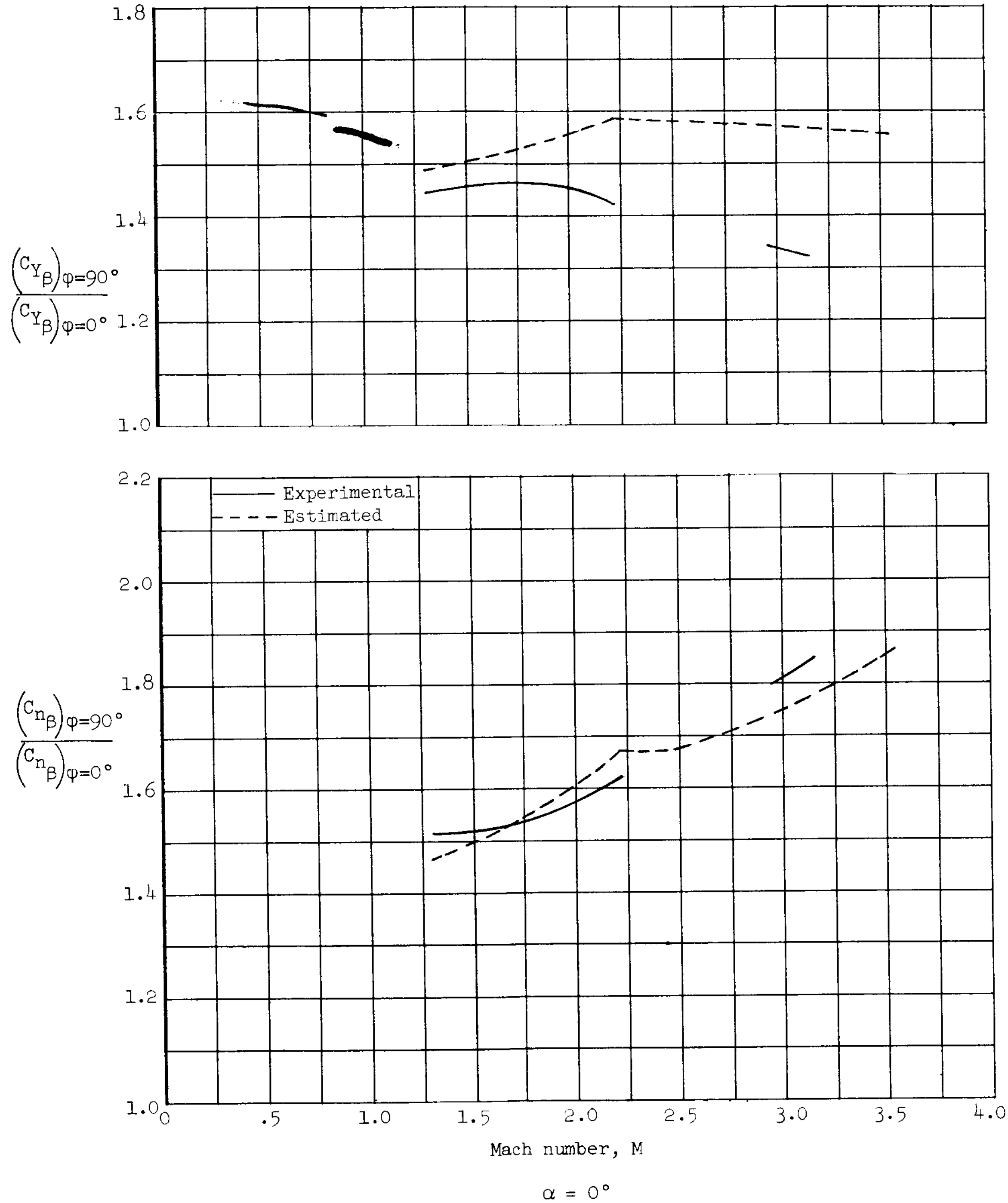


Figure 30.- Variation with Mach number of the effects on the directional characteristics with the triangular tips deflected resulting from the addition of the canard.

A 3 5 1

[redacted]



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1

Figure 31.- Variations with Mach number of the effects on the directional characteristics resulting from deflecting the triangular tips with the canard off.

[redacted]

[redacted]

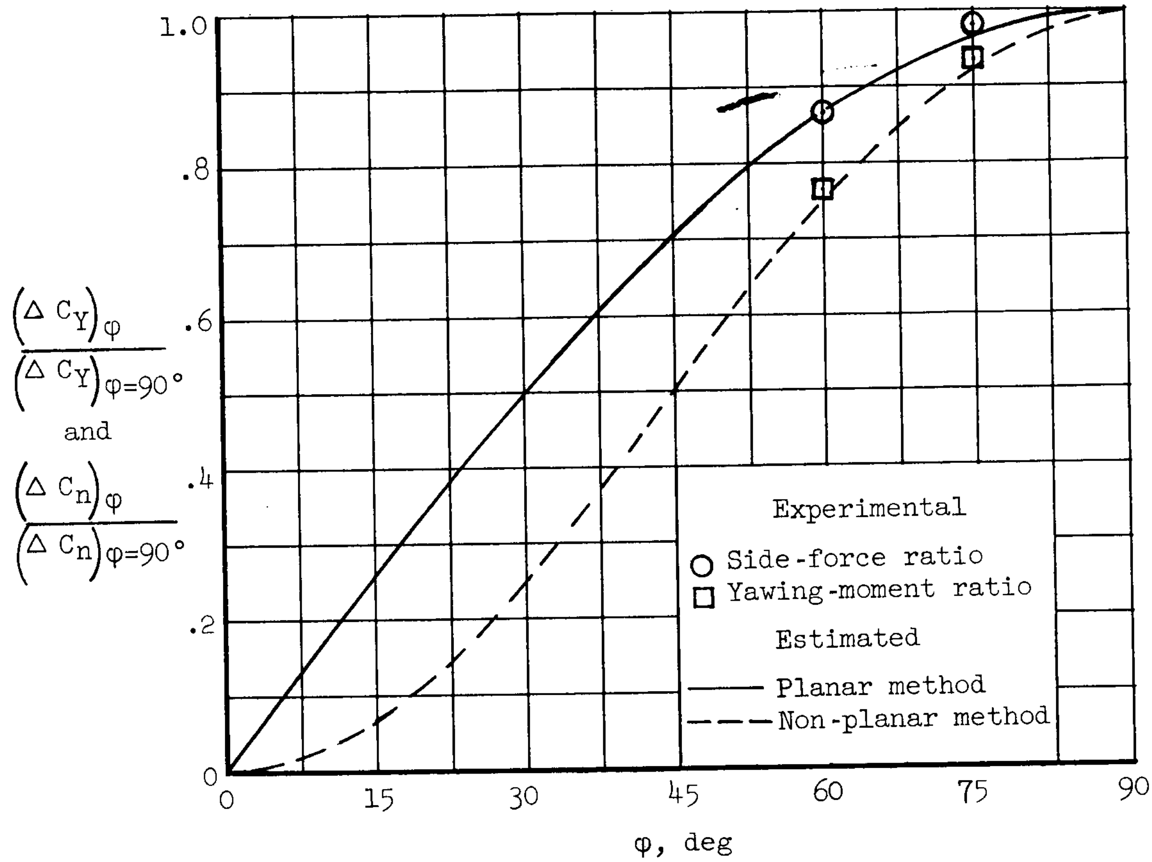

Figure 32.- Variation of side-force and yawing-moment ratios with tip deflection; triangular tips, $M = 3.06$, $\alpha = 0°$, $\beta = 5°$.

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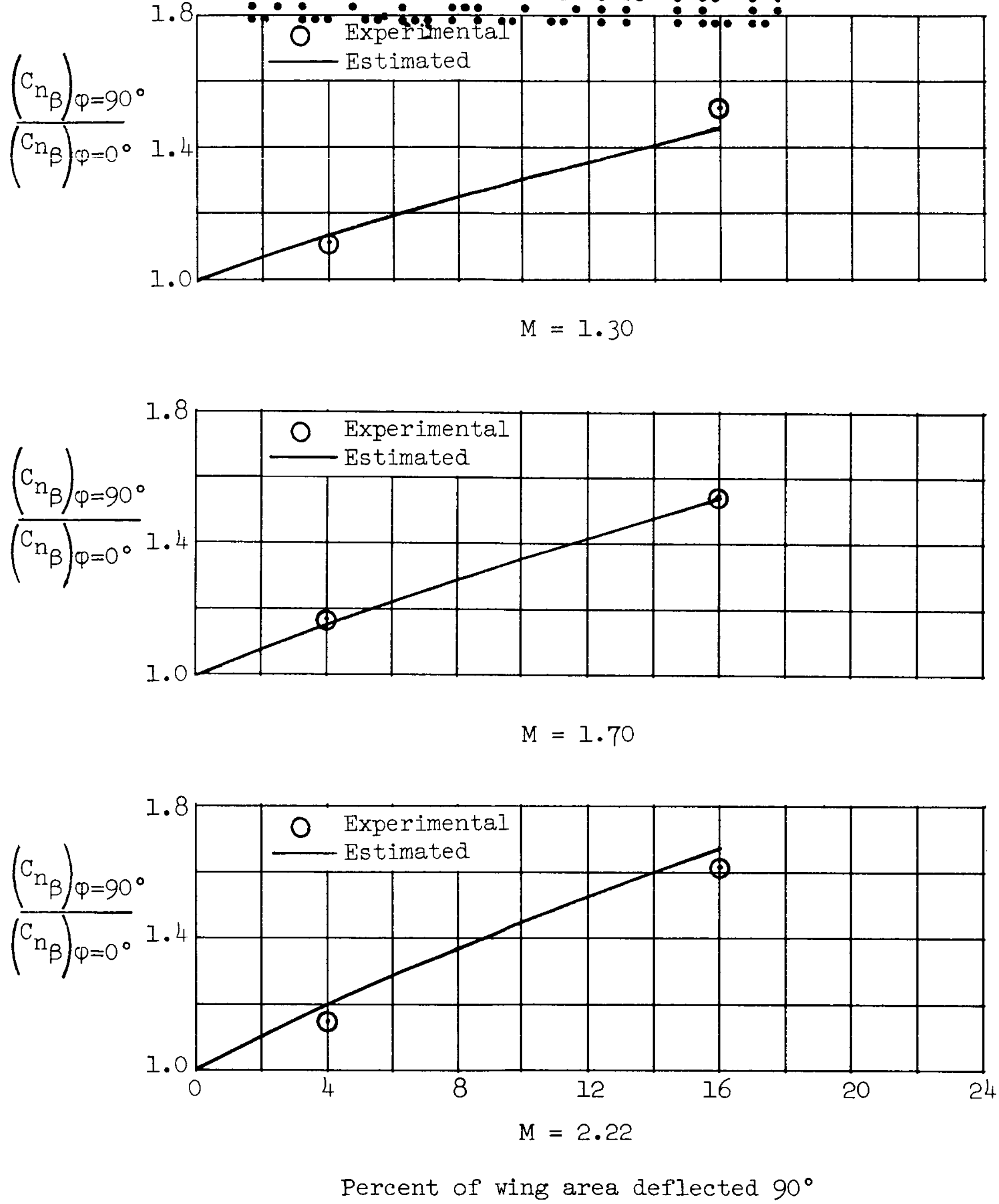

Figure 33.- Effect of amount of wing area deflected 90° on the yawing-moment ratio at $\alpha = 0°$ for triangular tips configurations with the canard off.

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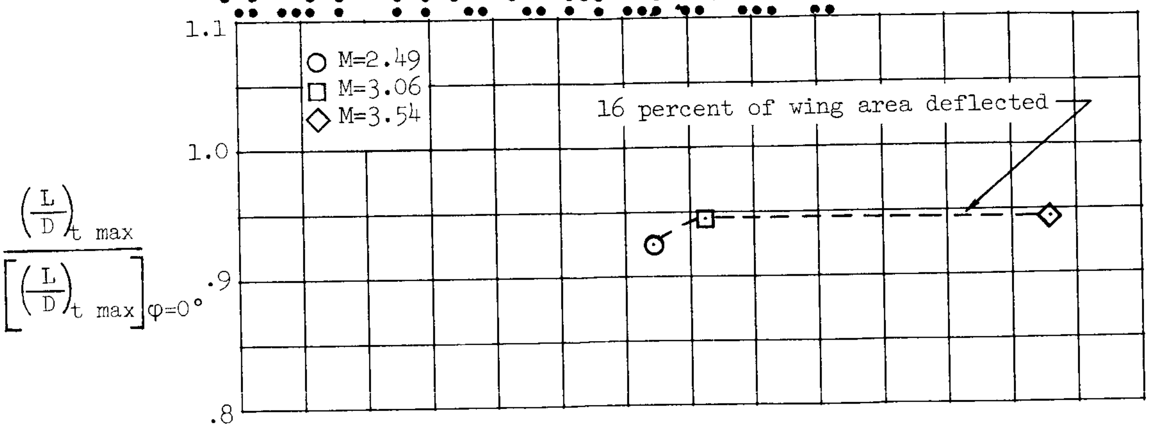
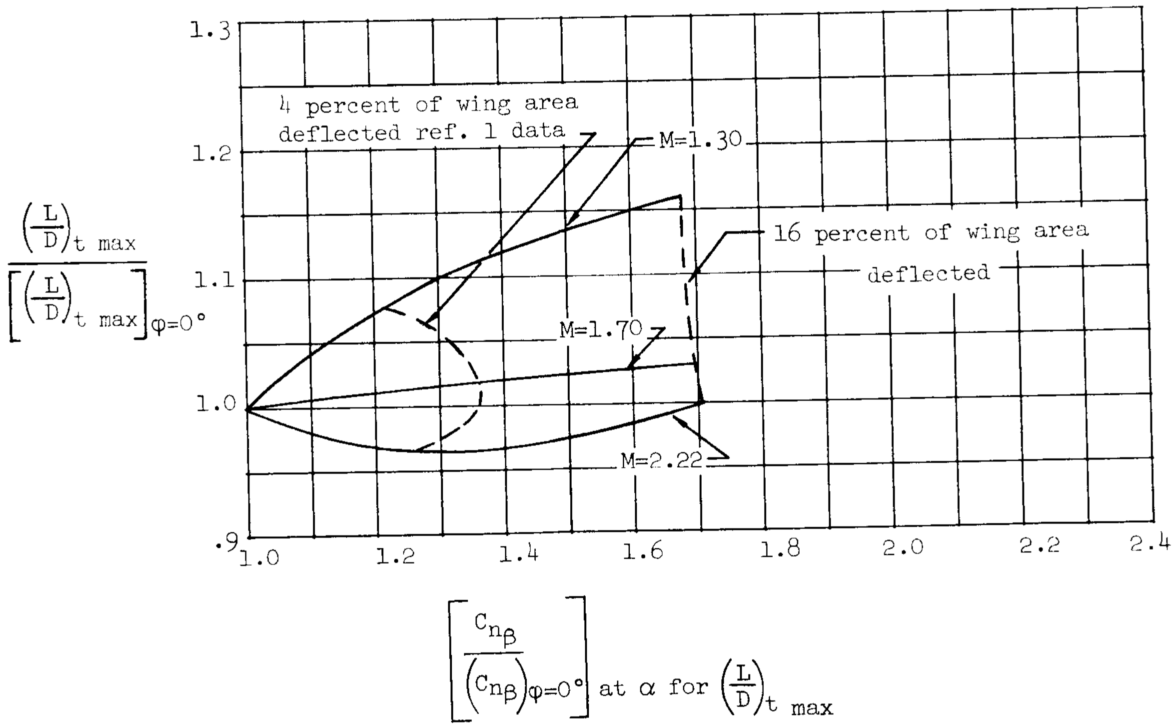


(a) Triangular tips, φ = 60°



(b) Triangular tips, φ = 90°

Figure 34.- Relative effects of deflecting the tips on the longitudinal and directional characteristics.

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